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GRADE / DEGREE

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Improving the Canadian Air Quality Index (AQI) Formulation:
Research Syntheses of Index Development and AQI Formulation Approaches, and Analytical Comparisons of AQI Formulation Options

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Improving the Canadian Air Quality Index (AQI) Formulation: Research Syntheses of Index Development and AQI Formulation Approaches, and Analytical Comparisons of AQI Formulation Options

by

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Thesis submitted to the Faculty of Graduate and Postdoctoral Studies in partial fulfillment of the requirements for the MSc degree in Epidemiology

University of Ottawa

October 3, 2007

Your file Votre référence
ISBN: 978-0-494-49196-6
Our file Notre référence
ISBN: 978-0-494-49196-6

ABSTRACT

There has been increasing evidence showing that current Canadian Air Quality Indices (AQIs) are not providing the public with accurate information on air quality conditions. In response, a process for improvement of Canadian AQIs was initiated in 2001 by Environment Canada and a broad multi-stakeholder community. This thesis work was conducted in an effort to aid this process and produce new knowledge in the area of AQI formulation and application. Two reviews were undertaken to identify the conceptual and measurement aspects of index development, and the current state of knowledge relating to AQI formulation. An analytical comparison of AQI formulation options was conducted using air pollution data from four urban centres in Ontario. The results suggest that there are a number of advantages associated with the health risk based formulation approach developed by Health Canada. Recommendations for Canadian AQI improvement are presented.

ACKNOWLEDGEMENTS

My parents, Kostas and Mata Economou are my inspiration and to whom I owe the most thanks for the completion of this thesis along with so many other things in my life that are too great to mention in just one page.

I share this thesis research and preparation of this paper with my thesis supervisors. Firstly, I am grateful to Dr. Yue Chen for being such a great thesis supervisor. I deeply appreciate his supportive and giving nature and admire his breadth of knowledge and commitment towards excelling his students. He introduced me to my co-supervisors and a research area which have supported and motivated me in my studies and life. Drs. Dave Stieb and Rick Burnett invited me to work with them and have provided unimaginable opportunities. I am in admiration of their commitment and sincere effort to work for the public good. To Dr. Stieb in particular, please accept my respect and gratitude for all that you have done for me. I feel honoured to have been mentored by you. I would also like to thank the entire team of stakeholders and collaborators working for the Improvement of Canadian AQIs. It was a pleasure to be part of such a collegial and supportive group. I am very proud of all the work that you have done and feel proud to have contributed to this improvement process.

I am also very thankful to have been surrounded by the supportive staff and faculty of the Department of Epidemiology and Community Medicine. I would also like to thank my academic colleagues and friends Fay, Sylvie, Mei, Kellie, Emily and Yelena for their friendship and encouragement during this process.

I would also like to acknowledge those individuals at Health Canada and the Ontario Ministry of Environment who provided their guidance, analytical support and resources for this thesis work.

Of course the completion of this thesis would not have been possible and would be meaningless to me without the support of the following people. Dariusz, thank you so much for your love and belief in me. You have provided me with constant motivation and support and have helped me in so many ways to reach my goals. Stacy, I have spent the most time in my life with you so far and because of that, I know I owe much of whom I am and my accomplishments to you, thank you. I am also extremely lucky to have the best group of girlfriends. Catherine, Mel and Tami thank you for always being there for me and encouraging me to persevere.

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LIST OF ABBREVIATIONS

AQI	Air Quality Index
AQIEPA	US Environmental Protection Agency Air Quality Index
AQIONT	Ontario Ministry of Environment Air Quality Index
Burnett 5p	AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2, SO_2, CO
Burnett 4p	AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2, SO_2
CO	Carbon Monoxide
GAM	Generalized Additive Model
HRBI	Health Risk Based Air Quality Index
HRBI 2p 24hr	Health Risk Based Air Quality Index 4-pollutant 24-hour formulation
HRBI 2p 3hr	Health Risk Based Air Quality Index 2-pollutant 3-hour formulation
HRBI 4p 24hr	Health Risk Based Air Quality Index 4-pollutant 24-hour formulation
HRBI 4p 3hr	Health Risk Based Air Quality Index 2-pollutant 3-hour formulation
IQUA	Index of Quality of Air (Canadian Air Quality Index)
MA	Meta-Analysis
MA 5p	AQI formulation based on Meta-analysis in relation to O_3, PM_{10}, NO_2, SO_2, CO
MA 4p	AQI formulation based on Meta-analysis in relation to O_3, PM_{10}, NO_2, SO_2
NAAQO	National Ambient Air Quality Objectives (Canada)
NAAQS	National Ambient Air Quality Standards (U.S.)
NAPS	National Air Pollution Surveillance network
NMMAPS	National Mortality, Morbidity and Air Pollution Study
NO_2	Nitrogen Dioxide
NPI	New Pollutant Index (Malakos and Wong,1999)
O_3	Ozone
OMOE	Ontario Ministry of Environment
PCA	Principal Components Analysis
PM	Particulate Matter
PM_{10}	Particulate Matter with median aerometric diameter less than 10um
$PM_{2.5}$	Particulate Matter with median aerometric diameter less than 2.5um
PSI	Pollutant Standards Index (U.S.)
RAQI	Revised Air Quality Index (Cheng et al., 2004)
S&T_Hyb	Root Sum Exponential with HRBI 4p 24hr average risk estimates
S&T_ONT	Root Sum Exponential with Ontario Ambient Air Quality Criteria
SES	Socioeconomic Status
SO_2	Sulphur Dioxide
Stieb 5p	AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2, SO_2, CO
Stieb 4p	AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2, SO_2
TEOM	Tapered Element Oscillating Microbalance

U.S. EPA	U.S. Environmental Protection Agency
WHO	World Health Organization
5-pollutant model	Health Risk Based Air Quality Index with O_3, $PM_{2.5}$, NO_2, SO_2, CO
4-pollutant model	Health Risk Based Air Quality Index with O_3, $PM_{2.5}$, NO_2, SO_2
3-pollutant model	Health Risk Based Air Quality Index with O_3, $PM_{2.5}$, NO_2
2-pollutant model	Health Risk Based Air Quality Index with O_3, $PM_{2.5}$

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1.0 INTRODUCTION

Canadians rely on the Air Quality Index (AQI) to convey messages about the present and forecasted level of air pollution in their area. The AQI transforms measured values of individual air pollutants into a single number and descriptive term. The public can use this information to mitigate the adverse health effects of air pollution by taking personal actions to minimize their exposures or activity generating emissions. Consequently there is an obligation to ensure that the information provided by the AQI is accurate and informative so people can take proper actions to protect themselves.

A number of scientific findings and national policy developments have identified shortcomings with the current Canadian AQI formulation and messaging system, and have questioned its ability to accurately inform the public. The main problem identified is that there is a misrepresentation of the health risk associated with air pollution levels[1,2]. In fact, the national Canadian AQI (IQUA) and the province specific AQIs, which are designed to serve as public health information tools, are not based directly on health related evidence. The observed health problems associated with air pollution are not reflected in the current Canadian AQIs. This problem was highlighted in a report by Toronto Public Health[1] where more than 92 percent of the air pollution-attributable premature mortality and hospitalization in Toronto was found to occur during AQI values of "very good" or "good". Thus, there is a need to work towards improving the current Canadian AQI. This need has been recognized by a variety of stakeholder groups and in 2001, Environment Canada and Health Canada initiated a process towards the improvement of Canadian AQIs.

The following thesis work was conducted in an effort to aid this process and produce new knowledge in the area of AQI formulation and application. Working in collaboration with a variety of different stakeholders has resulted in a comprehensive assessment and evaluation of the issues and implications associated with the development of a new Canadian AQI. The following document presents the results of a research synthesis of index development and AQI formulation options, along with an overview of a new health risk based air quality index developed by Health Canada and an analytical comparison of various AQI formulations. Recommendations are also presented for a new AQI formulation.

1.1 Statement of Problem

Several reasons have been identified to explain the problem of health risk misrepresentation associated with the current AQI, and the need for improvement[3-5]. The reasons are summarized below.

- *The AQI is not a health based index*. AQI calculations are based on National Ambient Air Quality Objectives (NAAQOs) or provincial targets, rather than health effects information.
- *Outdated Air Quality Objectives*. Some of the NAAQOs were developed in the 1970's and have not been updated since then.
- *Advances in air pollution health effects research.* There have been significant advances in air pollution health effects research, which have not been incorporated into the current Canadian AQI. In particular, no threshold has been

identified where human health effects do not occur for most if not all air pollutants.

- *Single pollutant driven.* The current AQI reports on only single pollutants, with no consideration for the additive or synergistic contribution of multiple pollutants.
- *Monitoring, reporting and forecasting technology improvements are not reflected in the AQI.* Despite the improvements that have occurred in monitoring, reporting and forecasting technology, there have been no significant alterations to the Canadian AQI.
- *Lack of a useful communication system.* The current AQI communication system fails to properly inform the public about the health effects associated with air pollution and to prescribe appropriate safety measures.
- *Ambiguous descriptive categories.* The descriptive categories currently used for reporting air quality conditions have been criticized for their ambiguous classifications. Public misunderstanding of air quality and the AQI needs to be addressed.
- *No evaluation system.* There has been no consistent method for evaluation of the AQI. Although shortcomings have been noted for a number of years, without a formal evaluation process there is a lack in accountability and progress in initiating actions to address the particular deficiencies.

1.2 Health Significance of Problem

Air pollution has a substantial impact on human health. Evidence for the adverse health effects of air pollution has been accumulating since the 1950's; there have been

extensive studies conducted in Canada and around the world that have linked air pollution to a variety of adverse health consequences. Public health and environmental agencies around the world, including the World Health Organization (WHO), the US Environmental Protection Agency (EPA), the UK Department of Health and Health Canada have concluded air pollution is a significant public health issue. Through air pollution health effects research, some of the effects of air pollutants on health outcomes have been identified and quantified. Still, there is continued interest in this area to obtain more accurate information and to understand the underlying mechanisms causing health effects from air pollution.

The health effects of air pollution range in severity from subtle sub-clinical effects such as biochemical and physiological changes, to hospital admissions for cardiovascular and respiratory complications and even premature mortality. The WHO estimates approximately three million people die each year globally due to air pollution[6]. In a study by Health Canada, it was estimated that there are 5,900 to 8,000 premature deaths annually associated with both short term and long-term air pollution exposures, representing approximately eight percent of all Canadian deaths. However, even this is believed to be a conservative estimate as the analysis only examined mortality impacts in selected cities[7]. In addition, the Ontario Medical Association (OMA) estimates there are approximately 16,000 hospital admissions, and 60,000 emergency room visits associated with air pollution for Ontario in 2005[8]. Moreover, clear linkages have been established between air pollution and reduced lung function, increases in asthma attacks and increases in respiratory symptoms and disease. Additional costs to society include restricted activity resulting in missed days at work, school and play and increased

medication use and doctor visits. Populations that are most vulnerable to these health effects include children, the elderly and those with pre-existing cardiovascular and respiratory diseases. The majority of these health impacts have been observed at levels below Canadian federal and provincial air quality objectives[1, 5]. From a population health perspective, some of the adverse health consequences represent common ailments and even a small increase in health risk could affect large numbers of individuals.

In the absence of ongoing efforts to improve air quality, this health dilemma will continue to persist into the future. Although reductions in some air pollutants have occurred over time, continued reductions face a number of challenges. Probably one of the greatest challenges will be in maintaining a concerted commitment and will from government, industry and the public to advance and sustain actions towards air emissions reduction. Without this united commitment it will be extremely difficult to manage air emissions reduction. Also, an increasing population, leading to increased consumption augments the potential for a greater amount of emissions from a variety of sources. Moreover, the population at risk is significant and growing, resulting in an even greater number of people affected by air pollution. According to the National Longitudinal Survey of Children and Youth, children with asthma aged 4-11 years have increased from 13.3 percent in 1994/95 to 15.2 percent in 1998/1999[9]. The population of seniors is also significantly growing at rates far beyond the rest of the Canadian population[10]. This trend is expected to continue because of increasing life expectancy. Thus, accurate and instructive public communication tools must exist that will be able to inform the public about air pollution. This way people can have the tools to take appropriate measures to protect themselves.

1.3 Literature Review: Air Pollution and Human Health

1.3.1 Key Air Pollutants

The focus of this review is five of the six so-called "criteria" pollutants: ozone; particulate matter; nitrogen dioxide; sulphur dioxide; and carbon monoxide, to which short-term exposures produce significant health effects. These pollutants have historically been associated with air quality criteria, or targets for ambient levels. There is an extensive historical database of concentrations of these pollutants in Canada and many other countries. These pollutants have been studied separately and in combination to identify their impacts on human health. While a comprehensive review of the health effects of individual pollutants is beyond the scope of this document, a brief summary is provided.

1.3.1.1 Ozone

The primary adverse health effects of ozone relate to the respiratory system. Lung function changes include increased airway reactivity, reduced tidal volume and decrements in forced vital capacity, and forced expiratory volume in one second and expiratory flow rates. Ozone is also responsible for increased respiratory symptoms and asthma attacks in sensitive individuals[11-13]. Recently, evidence has also emerged that ozone may contribute to the incidence of asthma and allergic disease[12, 14-17]. Moreover, ozone is significantly associated with mortality, hospital admissions and ER visits; however, less consistent mortality relationships are observed in the winter months[11, 18]. Links have also been observed between chronic ozone exposure and lung cancer, especially in males[12, 15]. Respiratory effects are greater in asthmatics but are also

observed in healthy adults and children[19]. Ozone toxicity occurs in a dose-dependent fashion with no observable threshold. Concentration, duration and activity level act in combination to intensify effects. Based on this evidence, the WHO declared it is not possible to assign an air quality guideline based on a no-observed-adverse-effect level or lowest-observed-adverse-effect level. They recommended the application of health risk information towards setting acceptable levels of exposure, in other words, that prospective benefits and costs of achieving alternative targets be evaluated along the continuum of a linear no-threshold concentration-response function[11].

1.3.1.2 Particulate Matter (PM)

Until the 1980s, there was only weak evidence showing that negative health effects can occur at low-level PM concentrations[17]. Since then, numerous studies have revealed that low level PM concentrations are linked to a variety of health effects. Particulate matter is heterogeneous in composition and has been classified in various ways according to size, chemistry and other characteristics. From a regulatory perspective, it is generally divided into three major categories, PM_{10} (particles with median aerometric diameter less than 10um), $PM_{2.5}$ (particles with median aerometric diameter less than 2.5um) and $PM_{10\text{-}2.5}$ or the coarse fraction, referring to particles intermediate in size between these two cut points. They are all inhalable particles but $PM_{2.5}$ can penetrate deep into the lungs. PM can initiate tissue damage and alter the defense mechanisms of the body against foreign materials[20]. Some of the adverse health effects include increased risks for development of respiratory diseases such as chronic bronchitis, increased risks for respiratory symptoms and declines in lung function. Many

studies have also shown a consistent relationship of PM_{10}, $PM_{2.5}$ exposures with premature mortality. Both $PM_{2.5}$ and PM_{10} have also been linked to increases in hospital admissions and ER visits[11, 21, 22]. Some investigations have also linked PM to lung cancer[23]. Individuals with existing respiratory and cardiovascular diseases also experience more severe symptoms. Longer-term exposures to PM during pregnancy are associated with low birth weight and there is some evidence for increases in infant mortality[16, 21]. Current studies are unable to define a threshold below which no health effects occur. Thus, the WHO has recommended against a guideline value for PM and instead suggests that risk managers use linear, no-threshold health risk functions (see above for ozone) for setting air quality management targets[11].

1.3.1.3 Nitrogen Dioxide

Nitrogen dioxide poses significant risks to human health. It is rapidly absorbed in the tracheobronchial region and because it is not easily soluble it can travel to the pulmonary region where it can initiate tissue damage[13, 17]. NO_2 is associated with pronounced decreases in pulmonary function and increased rates of respiratory illness. Even before effects are detected related to pulmonary dysfunction, there are significant increases in bronchial reactivity, indicating that NO_2 is associated with immediate effects[11]. Likewise, significant positive associations have also been found with daily mortality rates and hospital admissions[11, 12]. Research examining the effects of varied concentrations of NO_2 did not reveal a clear threshold, making it difficult to prescribe a guideline value[11].

1.3.1.4 Sulphur Dioxide

Sulphur dioxide has long been recognized as harmful to human health. Some of the worst air pollution episodes in history were due to elevated levels of SO_2. Some of the acute responses to SO_2 include airway narrowing leading to increases in airway resistance, decreases in forced expiratory flow rates and clinical symptoms such as shortness of breath and wheezing[24]. Studies have also shown that even at low levels of SO_2, there are daily increases in mortality and hospital admissions especially amongst those individuals suffering from pre-existing respiratory conditions[12, 17]. Many studies have focused attention on asthmatic patients because these individuals already have compromised respiratory systems. Increases in SO_2 have been shown to initiate asthma attacks in these individuals. Epidemiological studies of continuous exposure to SO_2 have been unable to identify any clear threshold for adverse effects. Yet, in controlled human lab studies of asthmatic patients exposed to SO_2 for periods ranging from a few minutes to one hour, minimum concentration values resulting in adverse effects have been found[11]. This indicates the potential presence of a threshold for short-term exposures and some types of health effects.

1.3.1.5 Carbon monoxide

The primary health effects associated with exposures to CO are cardiovascular and neurobehavioural. Those individuals who already have cardiovascular and respiratory diseases are particularly sensitive to elevated CO levels. The classic mechanism of CO toxicity is the binding of CO with hemoglobin to form carboxyhemoglobin (COHb). COHb reduces the blood's ability to carry oxygen

throughout the body[20]. However, it appears that other mechanisms are probably operating at lower levels of exposure. The Health Effects Institute multicentre study conducted in the U.S. found a dose-response relationship between CO and angina effects with no obvious threshold. Effects were observed at levels of the 8 hour CO NAAQS, calling into question the protectiveness of the prescribed standard[25]. Some epidemiological studies have also shown that moderate exposures to CO are associated with daily mortality and hospital admissions for cardiovascular, respiratory complaints and congestive heart failure[13, 17].

1.4 Literature Review: Approaches to Air Pollution Health Effects Research

At levels of exposure currently observed in Canada and other developed countries, adverse health effects of air pollution are subtle, and clouded by other concurrent environmental exposures, as well as factors mediating individuals' susceptibility. This section outlines approaches to air pollution health effects research, including an overview of how investigators attempt to isolate the effects of air pollution from other factors.

1.4.1 Research Approaches

There are two main approaches used in the assessment of health risks from air pollution: epidemiology and toxicology. Epidemiology is the study of the distribution and determinants of health-related states or events in specified populations, and the application of this information to the control of health problems[26]. Epidemiology thus has both descriptive and analytic dimensions. Describing the health of a given population

in terms of person, place or time variables provides information on those populations most at risk and can give clues to the potential causes of disease. Epidemiology also helps to explain health related states through the study of health determinants. This reflects its analytic dimension in providing evidence regarding potential causal factors of disease. The descriptive component often provides a rationale for action whereas the analytic component provides information on what needs to be done to reduce impact.

Toxicology has been defined as the scientific discipline involving the study of actual or potential danger presented by the harmful effects of chemicals on living organisms and ecosystems, of the relationship of such harmful effects to exposure, and of the mechanisms of action, diagnosis, prevention, and treatment of intoxicants[26]. For this discussion, the term toxicology will be used in its broadest sense to apply to all types of controlled experiments, including those conducted on humans. Traditionally, toxicological studies are conducted under controlled laboratory conditions where subjects are exposed to varied doses of toxic substances. The intent is to determine the functional, structural, and biochemical effects of toxic substances as a means of characterizing human health hazards[17].

Both epidemiology and toxicology have certain strengths and limitations in their assessment of human health risks. One of the main advantages of epidemiology over toxicology is that it provides direct information on human health in real-world settings. Thus, there is greater external validity in extrapolating the results of epidemiological investigations to other human populations. Additionally, epidemiological studies are preferable to controlled human lab studies in that they provide information on the effects of real-world exposures to pollutants and pollutant mixtures in people's real-world

settings. However, the accurate assessment of the exposure is often difficult because of the many factors influencing exposure. Some of the additional limitations associated with epidemiological studies include controlling for unknown modifying and confounding factors and the sensitivity of study designs to detect small effects.

In toxicological studies, exposure can be measured more precisely because experiments are conducted under highly controlled conditions. This allows for a more direct assessment of the effect of exposure on outcome. Toxicological tests are also highly sensitive and can be used to evaluate a wide variety of harmful effects. Animal studies allow for a wide range of pollutants and concentrations to be tested to determine any clear dose-response effects and biological mechanisms of causation. However, there is considerable uncertainty in extrapolating these results to human populations. Carefully controlled human lab studies are an alternative to animal studies providing information of the direct effects of pollutants on humans. However, for practical and ethical reasons, such studies are limited to small groups which may or may not be representative of the general population, and exposure is limited to concentrations that are expected to produce only mild responses of a short duration. Further, controlled human lab studies fail to capture the full suite of agents that humans are actually exposed to that could influence their response.

Evidence from both toxicological and epidemiological studies consistently demonstrates that air pollutants can result in a variety of adverse health effects. Since epidemiological evidence provides direct information on humans in their real-world settings and is associated with greater generalizability relative to toxicological evidence,

the results of epidemiological investigations are best suited to provide the health evidence base for public AQIs.

1.4.2 Air quality epidemiology

Epidemiological studies of the effects of air pollution on human health explore the associations between changes in air pollution levels and changes in the occurrence of different health-related outcomes. They can be particularly relevant from an air quality management point of view in that they provide quantitative information on the effects of ambient concentrations of air pollution.

1.4.2.1 Study Designs

There are several major designs that are used in air quality epidemiology. Four of the most common are described below:

1) Time-series studies are those in which the day-to-day variability in average exposure levels in a community is related to the day-to-day variability in the rate of an event such as death or admission to hospital. Because these types of studies can be conducted using readily available administrative data (e.g. mortality data from national vital statistics), hundreds of these studies have been published from around the world, providing a very large evidence base. These are ecological longitudinal studies with each community serving as its own control. As a result, the effect of individual confounders is minimized because factors such as age and smoking do not vary meaningfully from day to day in the population. However, other factors such as seasonal cycles in exposure and health outcome, and factors such as weather and influenza epidemics, which operate on the

same time scale as air pollution, can seriously confound the relationship between air pollution and health outcomes. The importance of dealing with these confounders appropriately was recently highlighted by the discovery of a statistical flaw in the computer program implementation of Generalized Additive Models (GAMs), which had become the preferred approach to adjusting for these confounders[27, 28]. In addition, since these studies are ecological in design it is important to note that the observed associations represent aggregate level associations, that may not necessarily represent associations at the individual level[26].

2) Cohort studies investigate the effect of cumulative exposures on health effects over a period of time. Although, cohort studies can examine both short term as well as long term effects, in air quality epidemiology these types of studies are often used to investigate the chronic effects of air pollution. An extended follow-up time increases the power of these studies because there is a larger denominator person-time base as well as an increased frequency of the disease condition occurring, minimizing the chance that a difference will not be found when in fact one does exist. . However, large sample sizes are required and considerable efforts are needed to ascertain the health status of these individuals over time. The associated time and expense mean that only a handful of these studies have been completed, and questions have been raised about the validity of extrapolating the results to different populations. In any case, because these studies are primarily based on long-term exposures, they are not applicable to AQIs designed to reflect short-term exposure.

3) Cross-sectional studies involve classifying subjects by differing levels of exposure and the associated health outcome at one particular time. The main issue with this design

is that unlike cohort studies, it is impossible to determine whether the exposure in fact preceded the health response, making it difficult to establish the existence of a causative relationship. Again, these studies are not informative with respect to the effects of short-term exposures.

4) Panel studies are generally considered to be a type of prospective cohort study in which the same set of participants are studied at multiple intervals of time[29, 30]. However, they can also be viewed as a special case of time-series studies, where a much smaller group of specific subjects is followed intensively over time to investigate the association between changes in daily pollution levels to transient changes in health status in individual subjects[15]. These types of studies are well suited to health outcomes such as respiratory symptoms or physiological parameters such as lung function or heart rate, which can be measured repeatedly. It is not suited to rare events like hospital admissions or unique events like death. Because these types of studies can assess effects of short term exposure, they are potentially applicable to the development of a short term AQI.

Since an AQI for daily public communication is intended to represent risks from short-term variability in exposure, the evidence base from studies of acute exposure was considered most relevant in a recent European assessment[31]. From the four study designs described above, the results of time-series or panel studies are therefore most appropriate for the development a health-risk based air quality index. Because time-series studies represent large-scale population effects, they might be considered superior to panel studies for this purpose.

1.4.2.2 Meta-Analysis

Given the hundreds of epidemiological studies linking air pollution and various health effects, the opportunity exists to summarize a wide variety of evidence, gaining a wider view than what can be achieved from the results of one or a few individual studies. One of the methods of summarizing the evidence is through meta-analysis. A meta-analysis is a statistical synthesis of the data from separate but similar studies leading to a quantitative summary of the pooled results. It involves a systematic approach to identifying, appraising, synthesizing and combining results of relevant studies to arrive at conclusions about a body of research[32]. Meta-analysis falls within the broader concept of systematic review. A systematic review also provides an assessment of the evidence but limits the statistical combination of results. Distinguishing between the two is important because a systematic review of the evidence is always considered appropriate and desirable whereas conducting a meta-analysis may sometimes be inappropriate or produce misleading results[33].

Meta-analysis provides many important advantages for evidence synthesis. First, a meta-analysis involves a systematic and explicit approach towards identifying and abstracting information from a collection of studies[34]. This makes it a formal and objective process so that subjective biases are reduced. Second, a meta-analysis can enhance the understanding of associations between exposures and their effects, which may not necessarily be apparent from individual studies[35]. In addition, meta-analysis can help increase statistical power so that small or subtle effects can be detected. Likewise, a meta-analysis can also form the basis of a sensitivity analysis to determine the influence of any single study or study type on the pooled estimate of effect. It can also provide an

overall summary of the exposure and disease relationship when it is not clear, and increases the generalizability of results by combining the results of many studies. Meta-analysis also offers greater opportunity for covariate adjustment and examination of effect modification. Finally, through meta-analyses data gaps can be identified and suggestions can be made for future areas of research.

There are also some important disadvantages that should be considered when conducting or making the decision to conduct a meta-analysis. First, it is difficult to resolve how study results that are from very different types of studies should be combined. Different study designs have different susceptibilities to bias and are of different methodological quality, which when combined can produce biased estimates of association. In addition, assumptions are made on the likeness of studies, which may be incorrect. Different studies do not measure exactly the same exposures and outcomes, hence combining varied measures to produce a single estimate may not be meaningful[34]. Also, the failure to consider important covariates can lead to bias and spurious conclusions. Moreover, although meta-analysis is based on a systematic process it is still susceptible to investigator bias. This type of bias could potentially influence the inclusion and exclusion of certain studies leading to different results. Another important and common problem faced with conducting a meta-analysis or any review is publication bias. This bias refers to the fact that positive and statistically significant results written in English are more likely to be published[36, 37]. Thus, these studies are more likely to be located and included in a meta-analysis, with the potential to ultimately bias any summary estimate of effect. It is important not to assign undue weight to a single summary measure as it does not adequately describe the findings when observed effects

in individual studies differ substantially[38]. Meta-analysis provides a summary of the results but not necessarily the truth. Considering the intended purpose, it has to be decided whether the acceptance of a partial truth is sufficient. These problems can contribute to reservations in regards to the credibility of meta-analytic findings.

DerSimonian and Levine[38] have also reported that there are increasing discrepancies between the results of meta-analyses and those of subsequent large randomized clinical trials. Evaluations of this differential have found that meta-analyses and large trials can disagree up to 10-35% of the time[39, 40]. The differences are not usually clinically significant since the same overall effect is observed but can be practically significant when an accurate estimate of effect is required. Large trials are often considered as the gold standard for testing the efficacy of a clinical intervention or a proposed exposure response relationship. Smaller studies tend to be associated with greater biases in terms of methodological quality and publication. However, the strength in small studies lies in their capacity to devote more attention to characterizing exposure and confounding factors. In the context of air pollution time series studies, large studies include pre-planned multi-city analyses such as the National Mortality, Morbidity and Air Pollution Study (NMMAPS), Air Pollution and Health: A European Approach (APHEA), and several multi-city Canadian studies by Burnett and colleagues. Stieb, Judek and Burnett[41, 42] found that results of their meta-analysis were generally similar to those of NMMAPS and APHEA. Thus, these reported differences between the results of meta-analyses and large studies may not be a problem for air quality epidemiological studies.

Meta-analysis can be a valuable exercise depending on the desired objectives. It is not always desirable to force diverse data into a single estimate to avoid the bias

associated with relying solely on a single study. Depending on the purpose, a review of only the most relevant studies may be sufficient. Bailar[34] reported no known instance where a meta-analysis led to a major policy change when a careful conventional review would not have led to the same change. Evidence from small and large studies as well as meta-analyses offer complementary information that can each be useful depending on the purpose[39].

Because meta-analysis offers many important advantages for evidence synthesis, this technique could potentially be applied to the selection of health evidence including concentration-response functions for an improved Canadian AQI.

1.4.2.3 Exposure and outcome assessment

The two key variables in any epidemiological study are exposure and outcome. Obtaining accurate measures contributes to the study's overall validity. For the assessment of short-term air pollution health effects, exposure assessment presents a particular challenge. Since the risks associated with ambient levels of air pollution are generally small, the exposure assessment needs to be as accurate as possible. However in terms of assessing exposure, there are practical considerations such as efficiency and cost. Recent studies have used personal exposure monitors to obtain a more accurate measure of exposure, but lack generalizability because these studies can only be performed on small numbers of individuals[17]. Most epidemiological studies measure exposure to pollutants from fixed site monitors. These data are limited in that individuals move about within their communities and most people tend to spend the majority of their time indoors. This can result in exposure misclassification errors. Still, epidemiological

studies of air pollution employing population level exposure estimates consistently show that varied levels of exposure result in varying levels of health outcomes, despite the occurrence of exposure misclassification. In the interest of generalizability and practicality, the use of exposure measures from fixed-site monitors is currently the best available method.

Health outcomes related to air pollution can be classified in terms of either acute effects, resulting from short-term exposures or chronic effects resulting from either short-term or long-term exposures. Acute effects range in severity from minor illness or discomfort to premature death. For the purposes of providing the public with a daily account of air quality and the associated health risks, acute effects are the relevant outcome group. For studies involving large numbers of individuals, health outcomes can generally be measured through the use of administrative health records when the health outcomes are severe enough to result in hospitalization or death. When they are collected as part of a centralized vital statistics system, records relating to the utilization of health care services and mortality generally follow common data collection and submission procedures contributing to greater data quality. Nonetheless, misclassification of cause of death[44, 45] or disease diagnosis[46-48] remains an important issue. This requires that caution be exercised in interpreting results for specific diagnostic groups.

1.4.2.4 Confounding Factors and Effect Modifiers

A confounding factor is defined as a quantity that is associated with both the exposure and the outcome under study, which, if unaccounted for, distorts the apparent relationship between them[49]. An effect modifier is a factor that interacts with the

exposure under study, altering its relationship with the outcome, meaning that the effect of the exposure differs at different levels of the effect modifier[26]. Some factors can be both confounders and effect modifiers. As an example, if not properly accounted for in the analysis of mortality time-series data, some of the effect of temperature on mortality might erroneously be attributed to ozone, since they operate on a similar time scale (confounding). At the same time the effect of ozone might be greater at higher temperatures (effect modification).

Meteorological and Temporal Factors

Time-series studies of air pollution and health are complicated by the effects of weather and time. Prior to the discovery of the statistical problems surrounding the computer program implementation of generalized additive models, most investigators used a suite of statistical techniques to adjust for the effects of time and weather. These included so-called parametric methods (moving average linear filters e.g. Shumway filter, natural or cubic splines, or Fourier series sine/cosine filters) and non-parametric methods (LOESS or locally optimal estimating and smoothing scatterplots, and spline smoothers). Non-parametric methods became the preferred method because they permitted investigators to flexibly model non-linear relationships, perhaps also reducing investigator bias because model specifications were dealt with in automated fashion by statistical software, rather than being determined by the a priori views of the investigators. While there was formerly a certain degree of confidence that many of these methods produced valid results, the recent issues surrounding generalized additive models have once again raised questions about the appropriate specification of weather and time in terms of time series studies[50]. In countries with a large degree of weather

variability such as Canada, results in time-series studies can be very sensitive to how weather terms are specified[51].

In addition to being an important confounder, weather may also be an effect modifier. At higher temperatures inhaled volumes increase, which consequently increases the intake of pollutants[17]. Moreover, during warm weather more people spend time outside, increasing their personal exposures to outdoor air pollution[11]. These variables exist within complex relationships that have not been consistently examined in the literature. There is also limited understanding of their interactions at the physiological level[50]. Thus, while it might be a desirable long-term goal to try and incorporate meteorological variables into an AQI, it would be premature at this stage.

Multiple pollutants

Models for estimating the effect of air pollutants on health can examine effects of pollutants singly or in combination. In multiple pollutant models, pollutants act as potential confounders where each pollutant's effect is adjusted according to the others. If the effect estimate of the pollutant remains relatively similar to its effect in a model containing only that pollutant then it is said to be stable and the effects of confounding are minimal. However, because the concentrations of pollutants can be correlated, individual pollutants in multi-pollutant models can behave in unusual ways, which distort the apparent "independent" effect of individual pollutants.

One of the major difficulties for a multiple variable analysis is dealing with the issue of multicollinearity. This can affect the least squares estimates, which are translated into representations of the associated risk. This problem occurs when there are near-constant linear functions of two or more of the predictor or regression variables[52].

Often times large correlations amongst the regression variables can be indicative of multicollinearity. If multicollinearity exists then the variances of some of the estimated regression coefficients can become very large and unstable resulting in potentially misleading estimates. This can be overcome by using only a subset of the regression variables that are not subject to multicollinearities. One of the methods used to determine the appropriate subset of regressors is principal components analysis (PCA).

The central idea of PCA is to reduce the dimensionality of a data set in which there are a large number of interrelated variables, while retaining the variation and relationship of the data as much as possible. This reduction is achieved by transforming to a new set of uncorrelated variables, the principal components[52-54]. This attempts to reduce any redundancy amongst variables. PCA has been widely used in atmospheric chemistry and meteorology because of the many different influential variables that are highly correlated. PCA simplifies the description of pressure, temperature, or other meteorological variable patterns over a large spatial area. PCA provides results in terms of the effects of each independent principal component or factor, rather than each individual pollutant, such that one factor might represent predominantly mobile sources versus stationary sources or long-range transport. The application of PCA in AQI development would benefit from further exploration.

Similar to weather, in addition to acting as confounders, other pollutants can also act as effect modifiers. For example, the effect of PM has been shown to differ at different levels of SO_2 in some studies. However, this has not been consistently examined in the literature.

Factors affecting increased risk

While the simple detection of effects of air pollution and subsequently the replication of these studies in multiple locations was the initial focus of air pollution epidemiology, attention is now turning to evaluating the nuances of these associations, including the existence of factors affecting the susceptibility of individuals to air pollution. These factors act on the concentration levels of pollutants to affect personal exposure or susceptibility and are related to individual characteristics that cause variance in the intensity of effects. Several examples of these factors are considered in this section.

Age and gender

The elderly appear to be particularly vulnerable because of their weaker physiological defense mechanisms and their increased prevalence of disease. Children are also at an increased risk because they have smaller airway passages, faster respiratory rates, less mature immune response systems and often spend more time outdoors than adults[11, 24]. Some studies have reported differences in effect by gender, but this has not been consistently examined in the literature.

Health status factors

Health status is also an important susceptibility factor. Individuals with pre-existing cardiovascular and respiratory diseases are especially vulnerable since they already have compromised respiratory and cardiac systems[24]. For asthmatics, those children and adults with mild or moderate levels of disease may be at an even greater risk than those with severe asthma because those with severe asthma tend to exert themselves less[11].

Health behaviours

People who exercise or do strenuous outdoor activities, including outdoor workers, are also at an increased risk of air pollution health effects[14]. This is because of their increased direct exposure, their increased breathing rate and increased oral breathing which indirectly results in an increase in exposure[11, 17]. In some studies, elevated risks for adverse health effects are also observed in cigarette smokers[55, 56].

Socio-economic factors

Socioeconomic status is generally measured by educational attainment, occupation and income, all of which have been reported to alter susceptibility to adverse effects of air pollution[57-61]. While the specific mechanisms through which these effects occur require further elucidation, one can speculate that people of lower socioeconomic status generally have poorer health, increasing their susceptibility to the adverse effects of pollution. They also have poorer access to health care resources, nutritional foods and medications for the control of disease.

Genetic factors

Most recently, studies have indicated that genetic factors can also play an important role in increasing susceptibility to air pollution health effects. This evidence comes from animal studies of ozone toxicity[15]. The observed individual variability in ozone effects amongst healthy and asthmatic individuals could be explained by predisposing genetic differences.

1.4.2.5 Dose-response assessment

Until recently, pollutant concentration-response relationships were based on the assumption of a threshold level below which there were no risks associated to health. The validity of this concept has come into question based on more recent evidence showing that health effects can occur at even low levels of pollutants that were previously considered safe. Based on their review of the literature for the Guidelines for Air Quality[11], the WHO concluded that a linear non-threshold dose-response relationship best characterized the association of O_3 and PM with various health outcomes. However, they cautioned against extrapolating this relationship beyond the available data, since there is some evidence to suggest that the relationship may change slope as concentrations increase or decrease beyond those levels studied. While in many time-series analyses, the primary analytical approach has been to assume a linear relationship between air pollution and health outcomes, many investigators have also conducted sensitivity analyses employing alternative assumptions about the shape of the concentration-response relationship. In particular, in their re-analysis of the NMMAPS data, the investigators found that among alternative functional forms, linear, no-threshold concentration-response relationship best described the relationship between particulate matter and cardiovascular-respiratory mortality[62]. The implications of this evidence are particularly relevant from an air quality management perspective, in that the use of cut points below which there are no effects, is not supported by the evidence. Instead, pollutant-concentration response relationships can be used to provide information on the associated health impacts from pollutant levels over a continuous range of concentrations.

1.4.2.6 Time-averaging issues

Air pollution exposure measures are generally obtained from averaging pollutant concentrations over time. This is done to obtain an average estimate of exposure that an individual might experience over the course of a day or a few hours. Time averaging also provides a more stable estimate of exposure since monitors can be sensitive to other external factors. Most air pollution studies that have examined the effect of using different time averages for a measure of exposure, have found that the health risk estimates obtained from studies using shorter averaging times (1 and 8 hours) are highly correlated with studies using longer averaging times of 24 hours.

In epidemiological studies of air pollution and mortality or hospital admissions, 24-hour time averages of pollutants are generally used as the measure of exposure. This is because the outcome measures are recorded on a daily basis. In the reporting and forecasting of air quality, shorter-time averages are preferred so that the public can be provided with more current information. It may be possible to explore the effect of shorter-time averages by using health outcome data related to emergency room visits. These data are generally recorded on an hourly basis so they can be linked to hourly or a few hours worth of exposure data. Until additional analyses are completed however, different options such as scaling between 24-hour averages and 3-hour average values could be explored to obtain shorter-time estimates.

1.4.2.7 Lag Structure

Lag time is the time between the occurrence of an exposure and its resulting effect. It is particularly important for the study of population level health impacts of air

pollution since it can take time for health effects to occur. At this point, there is no consensus on the "true" lag structure for health effects among the various air pollutants. Indeed, lag times could plausibly vary among different health outcomes and population groups, for the same pollutant. This makes it impossible at this time to precisely predict, in the context of AQI messages, when effects would be expected to occur, relative to exposure.

1.5 Brief History of AQI Improvement Process

In response to the current problems associated with Canadian AQIs and the recent advancements in air pollution health effects research, Environment Canada organized a multi-stakeholder workshop in June 2001 towards creating an improved nation-wide AQI. From this workshop, the process for improvement of Canadian Air Quality Indices was initiated with the creation of an AQI management committee comprised of a broad stakeholder community.

A progress report was submitted to the 2002 Toronto Smog Summit outlining recent recommendations on the next phases of AQI improvement. Based on these recommendations, Health Canada has been working on developing a new Canadian AQI known as the "health risk based AQI" that incorporates epidemiological information on air pollution and health risks. Recent scientific analyses in support of this work were presented to the AQI management committee, selected scientific advisors and members of the AQI Health Aspects Working Group at a workshop in June 2003. A range of views and levels of confidence were expressed in the work and the direction of the new AQI. It was felt that still more work remained to be done on the scientific aspects of the

new AQI. Health Canada has taken on this challenge with further development of a health risk based index to address some of the stakeholders' concerns.

A working group was also created to work on the improvement of the health messaging component of the AQI improvement process. In 2004, Health Canada funded an integrated study of public perceptions of air quality for the purposes of informing the formulation of air quality messages. The strategy included post-air quality event surveys, a national post-smog season survey, mental models analysis, focus group testing and an air health message development workshop.

1.6 Summary: Progression of Understanding

There has been substantial progress in air pollution health effects research over the past several years. Interest in this area has been sustained because of the current public health burden and the potential for even greater future consequences. Adverse health effects have been found to occur at even low levels of air pollution, which were previously regarded as safe. This means that at all levels of air pollution there is some associated hazard. Consequently the validity of incorporating prescribed limit values or standards into the AQI has been questioned[1]. Instead of limit values, the use of pollutant-concentration response relationships for different health end points can provide more accurate information for taking effective action to reduce effects. In addition, it has been observed that health effects are complicated by the additive or synergistic contribution of multiple pollutants. Exposure to pollutants with similar toxic effects may result in an additive response, which is not reflected in AQI formulations currently in use in Canada[1,5].

Further progress in air pollution health effects research is needed to improve our understanding of exposure-mediating factors, toxicity of different components, pathophysiological mechanisms of effects, susceptibility factors and effects of multiple pollutants. However, our understanding has progressed so far as to realize that there are major deficiencies in the current AQI. Using the best available current evidence, substantial improvements can be made to provide a more informative AQI to the public.

1.7 Thesis Outline and Contribution to the Field

By building on the work already done by the AQI working groups and management committee, this thesis work offers a contribution to the process of AQI improvement in Canada for consideration by the AQI management committee. There are four main parts to this thesis: 1) A review of the conceptual and measurement aspects of index development; 2) A review of air quality index formulations; 3) A detailed methodological overview of the health risk based AQI; and 4) An analytical comparison of various approaches towards AQI formulation.

The first review was undertaken with the purpose of identifying and understanding the important considerations for index development and establishing evaluative criteria for proposed or existing AQIs. The second review was initiated to identify the potential options for an improved Canadian air quality index and also to identify any general gaps or inconsistencies existing among different instruments along with their advantages and disadvantages. This work serves as important background information for this thesis and for the development of an improved Canadian AQI in identifying the underlying theoretical considerations for index development as well as

identifying the international work done towards AQI development and practice. A review of different AQI formulation methodologies also serves to contribute to the rationale for a new methodology in AQI formulation. The overview of the health risk based AQI formulation is presented since the detailed methodology and groundwork for this formulation is reflective of the process of developing a new index formulation. The analytical comparison of different AQI formulations offers a preliminary examination of index properties highlighting some of the strengths and weaknesses associated with each approach. The final aspect of this thesis, which places the work in its practical significance, is the detailed discussion and implications of the overall findings.

The thesis has been organized to reflect these four main parts first beginning with an outline of the goals and objectives of the thesis work. Sections 3, 4, 5 and 6 describe the results and present individual discussions for the three main thesis components. The seventh section provides a discussion of the results of each thesis component and discusses the overall implications of the findings. Finally, the eighth section of the thesis presents the conclusions of this work and offers recommendations for the improvement of Canadian air quality indices.

1.8 Relevance to Epidemiology

The process for improvement of Canadian AQIs is an example of a policy specifically associated with health implications. The quantitative formulation of the AQI requires a health evidence base to make it a relevant policy tool. The associated messaging framework for the AQI also requires that health protection serve as the primary focus. As such, the development process should be guided by a health-evidence

base drawing on epidemiologic dimensions. The study of a population level health issue such as air pollution, benefits from the knowledge and application of epidemiology. The research synthesis, quantitative analytical comparison, critical evaluation of formulations and the interpretation of these results towards the development of a public health information tool, are all epidemiological dimensions contributing to this thesis.

2.0 OBJECTIVES

Primary Objectives

The primary objectives of this thesis work are:

1. to determine the current state of knowledge on the conceptual and measurement aspects of index development;
2. to identify the current state of knowledge and practices relating to air quality index formulation and application;
3. to conduct a quantitative analytical comparison of various approaches towards AQI formulation; and
4. to provide recommendations for a new Canadian AQI formulation.

Secondary Objective

The secondary objective of this thesis work is:

1. to contribute to the process for improvement of Canadian AQIs by producing relevant work for consideration by the AQI management committee.

3.0 A REVIEW OF CONCEPTUAL AND MEASUREMENT ASPECTS OF INDEX DEVELOPMENT

3.1 Summary of Objectives

The objective of this review is to determine the conceptual and measurement aspects of index development. This information will help identify the key considerations when undertaking index development. Moreover, this review will help establish criteria for the analytical comparison of AQIs in section six of this thesis.

This section will begin with a discussion of index definitions and goals. Next, an overview of index development will be presented along with some important key considerations and specific examples for AQI development. Some of the associated challenges with index development will also be presented. To conclude, suggestions for evaluation criteria that would be applicable to a comparison of AQIs will be described.

3.2 Introduction

Indices are highly valued for their ability to communicate complex and large amounts of information quickly and easily. This has led to the widespread development of indices across a range of disciplines. Yet, there are no clear guidelines for the development and evaluation of indices. Other summary measurement tools such as scales and indicators are closely related to indices and have had more documented developmental progress. Thus, some of their guidelines and conceptual aspects are also reviewed here, for index development consideration.

Four key aspects are identified in the definition of an index or indicator. First an index is designed to simplify. Ott[63] defines an index as "a means devised to reduce a large quantity of data down to its simplest form, retaining essential meaning for the

questions that are being asked of the data". Second, an index provides more information than what is directly being measured or observed[64-66]. This allows conclusions to be drawn about endpoints that cannot be measured directly. For example, measuring outdoor air quality is not achieved through a singular measure. Its measurement relies on a number of variable components, including different individual air pollutants each of which contribute to the overall concept of outdoor air quality. Third, an index is a communication tool. It is designed to deliver information in a useable and understandable form[63, 67, 68]. Often times the audience of indices are the public or policymakers that are trying to understand the issue and quantify its status over time and space. Thus, the communication components of an index are important elements of its subsequent use and interpretation. Finally, the Commission on Geosciences, Environment and Resources (CGER)[67] has added that indicators are representative of something of interest. McDowell and Newell[69] add that the development of health indicators is based on the choice to reflect problems of social concern, ones for which improvement is sought. Thus, the information available from an indicator or index is reflective of an issue of concern and is used to aid decision-making surrounding the issue. In Briggs[70] and Environment Canada and Health Canada[71] some specific goals of environmental health indicators were highlighted. They state that indicators are needed:

- to help monitor trends in the state of the environment and health;
- to compare different areas or countries;
- to monitor and assess effects of policies;
- to help raise awareness across different stake-holder groups; and
- to help investigate potential links between the environment and health.

These goals highlight some of the important ways in which indicators can assist policymakers and the public in understanding environmental health issues. This contributes to a more informed approach when decisions or future actions surrounding these issues need to be made.

Indices, indicators and scales are all examples of measurement tools. They are all closely related; however, there are some differences in their intent, construction and interpretation. Indicators can serve as measurement tools themselves or can be used in combination as the variable components making up an index. Examples include infant mortality rates and life expectancy at birth. With the use of health statistics, these population health indicators can be calculated. A scale, similar to an index is also made up of individual variable components. These variable components when combined provide information on concepts that cannot be measured directly. However, the relationship of the variable components to the concept being measured differs between an index and a scale. The variables underlying a scale are dependent on the concept being measured, whereas the variables underlying an index are independent of the concept being measured[72, 73]. For example, DeVillis[72] describes the measurement of optimism in terms of scale measurement. The components that make up the optimism scale such as levels of agreement to statements such as "In uncertain times, I usually expect the best" are presumably dependent on the state of optimism itself and thus a higher level of optimism causes an increase in the scale variable components. On the other hand, socioeconomic status (SES) is an example of an index measurement. SES is composed of the variable 'level of education'. Level of education is independent of the concept of SES since SES does not cause more or less education. Although these theoretical

differences exist between scales, indicators and indices, in the area of health measurement these items are often used interchangeably and cannot be distinguished by the preceding definitions.

3.3 Methods

Several search strategies were used to identify reference material on index development and air quality index development to be included in this review. Literature searches using Web of Science, Medline and the Environmental Sciences and Pollution Management databases were performed for all English citations from the earliest respective database coverage date to November 2003 that contained one of the following keywords: "index theory", "index development", index construction", "measurement theory", "scale development", "scale construction", "indicator development", "indicator construction", "environmental indices", "air quality index", "air pollution index", "air quality indicator", "air pollution indicator " "air quality management", and "air pollution management". The University of Ottawa and University of Toronto library catalogues were also searched for English references containing one of the above keywords. The reference lists from all relevant references were also searched manually to find any further relevant references for inclusion in this review. All documents obtained from the above sources were examined and were included in this review if they provided a description or information on the process, components or theoretical considerations for index, scale, indicator development or AQI development.

3.4 Overview of Index Development

Index development is guided by a set of key steps and considerations. In reviewing the literature and related literature on index development one of the most frequently cited starting considerations is the identification of a guiding conceptual framework for the index and representative issue. The framework presents a general overview of the steps and factors contributing to the index development process. This sets the stage for the entire process without detailing the specifics of each step or consideration.

Frameworks for Index Development

Briggs of the WHO[70] presents a profile for environmental health indicators that provides guidelines on indicator development. The profile is divided into two sections: a general indicator profile and an example indicator. The general indicator profile lays out the foundations for indicator development and includes: 1) a specification of the environmental health issue that the indicator addresses; 2) the rationale and role behind the indicator; 3) linkage with other indicators; 4) alternative methods of defining and constructing the indicator; 5) related indicators; 6) sources of further information; and 7) relevant agencies involved in indicator development and use. The specific components of the example indicator profile consist of: 1) a detailed definition of the indicator; 2) a description of the relevant underlying concepts; 3) the specific data needs and sources; 4) the method of computation; 5) the units of measurement; 6) the potential scales of application; and 7) a description of the ways in which the indicator can be interpreted. This profile illustrates the analytical and practical considerations that are required in the development of indicators.

In 2000, a multi-disciplinary group chosen by the Governing Board of the U.S. National Research Council developed a general checklist to help with the development of ecological indicators[67]. The entries in the checklist included: 1) general importance; 2) conceptual basis; 3) reliability; 4) temporal and spatial scales of applicability; 5) statistical properties; 6) data requirements; 7) necessary skills of collectors of data; 8) data quality control; 9) archiving and access; 10) robustness; 11) international compatibility; and 12) cost-effectiveness. This checklist can be used to assess the potential importance of a proposed indicator, its properties and limitations, and how the indicator might be used.

Netemeyer et al.[73], DeVellis[72] and Spector[74] have provided similar overviews for scale construction. The initial phase is concerned with concept definition and the generation of a variable component pool. Then a set of measurement issues is developed for consideration. Next, the scale is developed and pilot tested. Finally, the scale is evaluated with particular reference to validity and reliability testing.

Diamantopoulos and Winklhofer[75] also focus attention on the variable components of index construction. They consider four issues to be critical in the development of indices. These are: 1) content specification to describe the issue the index is trying to capture; 2) indicator specification to determine the set of variable components relating to the issue of interest; 3) indicator collinearity to help understand the influence of each variable to the underlying issue and to assist with variable reduction; and 4) external validity testing to assess the suitability of index variables for the index.

The above frameworks reflect some common steps towards index development. The key steps for index development are summarized in further detail below, drawing on information from other relevant literature on index development.

3.4.1 Key Steps for Index Development

Defining the Purpose

The primary step in index development is defining the purpose of the index[11, 65, 69, 76]. This is probably the most fundamental aspect since it will help guide the overall construction of the index and consideration of relevant factors. The purpose should reflect the general importance of the concept being measured to help understand the significance of the index. In addition, the purpose should outline the scope of the index indicating the intended users and the spatial and temporal resolution. With a clearly defined purpose indicating how and by whom the index will be used, the developmental process will be grounded to a common goal or set of goals. The purpose will be influenced by the policy-relevance of the issue that is intended to be measured. Ultimately, the purpose needs to be in accord with societal and political values and the development of the index will only be considered useful if it relates to an issue of future interest or concern[11, 68].

Literature Review

The next major step in developing an index is to conduct a literature review to ascertain if an appropriate index already exists for the desired purpose[74, 77, 78]. If no such index exists then this gives greater justification for the development a new index. However, if an index already exists then a newly proposed index needs to show some

theoretical or empirical advantage over the existing index to be considered useful[73]. This is referred to as incremental validity. Netemeyer et al.[73] state that a new index should either capture the index concept more accurately or be more efficient in its capture than the existing index. Increased efficiency can relate to simpler variable component determination or end-use.

Conceptual Basis

An underlying conceptual basis should also be described for the index. This will inform the scope and selection of candidate variable components to define the index[65, 67, 68]. In this description of the conceptual basis it is necessary to describe the index concept and explain why it cannot be measured directly. This requires a strong understanding of the index concept. As previously stated in the example of measuring outdoor air quality, this issue is not measurable on its own, as it is determined by a number of variables. The identification of index variables relies on establishing a context for the issue of air quality. Air quality can be examined from multiple perspectives such as the health significance, environmental significance or economic significance. It is important to decide on the relevant perspective so that the selection of variables can be grounded in a defined evidence base. In addition, a description of how the index is intended to behave to reflect its index measure should be provided (e.g. for an AQI, higher values might mean worsening air quality).

Variable Selection

The next step in index development is the selection of variables that will be used to formulate the index[72, 75, 76, 78]. This step is guided by the conceptual framework and requires that there be a reasonable scientific basis for the selected variables. Taking the

example of air quality and air pollution health science again, these issues have been studied by many researchers in many different countries. Numerous studies have been published on the adverse health effects associated with air pollutants. For AQI variable selection, Ott and Thom[79] stated that an AQI should relate to ambient air quality standards, and Garcia and Colosio[80] also recommended this criterion. Today all of the AQIs in practice rely on some form of guidelines or standards for their construction. This criterion may not satisfactorily reflect the current health evidence showing a no threshold level effect of air pollutants on health. Thus, the original validity of this criterion is questionable. Rather the criterion can be extended to encompass a more general perspective, that of an AQI requiring a scientific and health evidence base.

Along with the science driving the choice of index variables, monitoring capacity and data availability are also important considerations for the selection of index variables[81, 82]. This will involve determining the potential sources of data and a judgment of their relative quality in contributing information to the index[67, 70]. If certain variable information is not available due to either resource or technological constraints, then their inclusion in the index is not feasible. This does not mean that with future advancements these variables should not be included; rather an index should be amenable to change[83].

As previously mentioned, the variables in index development are the determinants of the index. Thus, Diamantopoulos and Winklhofer[75] argue that variable selection should cover the entire scope of the index concept (i.e. what the index is trying to measure) because the failure to include even one variable could change the meaning of the index concept.. After all the variables have been considered, they suggest analyzing the variables for collinearity to identify any variables that may contain redundant

information. However, with excessive collinearity among variables it is difficult to assess the individual influence of each variable on the index concept. This presents a quantitative method for variable selection and reminds us that a rationale should be provided for each variable that is included in the index along with those variables that were considered but not included in the final index.

Variable Aggregation

The next major step in index development is variable aggregation. This includes the methodology for combining the variables and a judgement of the relative importance of each of the variables. This step requires a thorough understanding of the index variables and how they relate to the index concept as well as each other. The major components of variable aggregation are summarized as normalization, aggregation, weighting and valuation. Before the variables can be combined they need to be transformed or normalized so that they can be compared in a meaningful way. This does not necessarily mean that the variables need to have the same measurement unit; rather, through normalization the measurement units of the different variables are made similar. For the majority of AQIs, the variables that make up the AQI are normalized by a prescribed air quality guideline or standard. Next, the variables are aggregated or combined. This is where the mathematical model for combining the variables is described. The main methods of AQI aggregation and an assessment of the benefits and limitations will be discussed in section four of this thesis. Variable aggregation also involves a determination of any weighting factors for the index variables. This is a key component to variable aggregation since it assigns a relative importance to each variable for the index concept. For AQIs this can take the form of prescribed weights associated

with each variable or different standards associated with each pollutant. The final step in variable aggregation is valuation. In this step, index values are qualified for interpretation. For example, index values are compared with a predetermined classification of what constitutes good or poor values[76].

Validity and Reliability Testing

Arguably, the most important step after the index formulation has been developed is to assess the validity of the index. Index validation is concerned with whether the index actually represents its intended measure[69, 74, 77, 84]. The concept of validity is itself broad and consists of many different types of validity. Generally there are three types of validity that are commonly cited in index and scale development literature. These include: construct validity, content validity and convergent validity.

Construct validity involves an assessment of how well the index reflects its conceptual basis and behaves accordingly[72, 73]. This can also be thought of as the accuracy of the index. For example an AQI should reflect to the best of its ability true air quality conditions, so that the public is properly informed. Two important factors mentioned in the discussion of AQI accuracy are ambiguity and eclipsity[85, 86]. *Ambiguity* is defined as "the capability of being understood in two or more ways" and *to eclipse* is defined as "to obscure" or "to render dim by comparison" [87]. When these factors are described in relation to AQIs, the result is a false impression of air quality conditions. Ambiguity signals less polluted air as highly polluted, and eclipsity indicates good air quality conditions when conditions are poor[85, 88]. Since the importance of air quality categorization is associated with the ability to communicate those air quality conditions that are high/poor versus non-high/poor air quality conditions, this binary categorization

can be thought of in terms of epidemiological sensitivity and specificity. Sensitivity of an exposure measurement is the probability that someone who is truly exposed will correctly be classified as exposed by the measurement tool[89]. The false positive rate is the probability that someone who is truly unexposed will be classified as exposed which parallels ambiguity by declaring non-poor air quality conditions as poor. Specificity is the probability that someone who is truly unexposed will be classified as unexposed[89]. The false negative rate is the probability that someone who is truly exposed will be classified as unexposed. This corresponds to air quality eclipsity by signaling poor air quality conditions as non-poor. An accurate assessment of false positives and false negatives is currently not possible among air quality indices since there is no gold standard to compare to and there is a health risk associated with all air quality levels. However, a relative assessment of false positives/negatives among AQI's can be made based on whether each AQI has incorporated current air pollution health risk evidence to inform air quality conditions.

Reported air pollution levels or the reported levels of any index measure can have important policy impacts. In the case of an AQI, the intent is that the reported air pollution level will help guide people's actions towards mitigating their air pollution exposures. Reported AQI levels are also known to influence political and economic actions related to pollution alleviation through rolling blackouts, driving restrictions and/or industry production interruptions[90]. Therefore, it is important that an index minimize ambiguous/false positive and eclipsed/false negative measures.

Content validity refers to the degree to which the index variables are relevant and representative of the index measure[73, 84]. As previously mentioned under variable

selection, the index variables are chosen based on a connection to the conceptual basis of the index measure. Assessing the content validity of the index variables to the index concept can provide additional justification either for their inclusion or exclusion from the index.

Described as a specific aspect of construct validity, convergent validity assesses the extent to which the index and some other measure that is used or accepted in practice to measure the same concept, agree with each other [69, 78]. Ideally the other measure is a gold standard to which the index can be compared; however, with air quality indices as is the case with most other indices, there is no gold standard. In this case, existing indices designed to measure the same concept can serve as measures of comparison.

As previously mentioned, the case of designing an improved index also involves a special consideration for incremental validity. Incremental validity is described as the addition of some theoretical or empirical advantage over an existing measure[73]. This can result from a better understanding of the conceptual basis for the index and thus lead to refining the selection of relevant index variables, or a refinement in the methodology for variable aggregation so that the index provides a more accurate assessment of its intended measure.

Diamantopoulos and Winklhofer[75] have suggested a method for external validity testing of a proposed index. This method involves the use of the multiple indicators and multiple causes (MIMIC) model introduced by Hauser and Goldberger [91] and Joreskog and Goldberger. In this model, index variable components act as direct causes of the index measure, and the index measure is related to one or more "reflective" measures. The reflective measures are chosen to represent effects of the index measure. The index

variable components are then fit to a model representing the reflective measure. Good model fit can be taken as supporting evidence for the validity of the indicators forming the index. For example, in an AQI, the index variables are represented by the various air pollutants, the index measure is the overall assessment of air quality and the reflective measures are represented by health outcomes such as mortality or hospitalization. The AQI value from the index formulation could be fit to a model representing a health outcome to determine the overall goodness of fit of this model. However, in the case where the reflective measure is used to develop the index variables and their assigned weights, this could be seen as a circular evaluation. Good model fit would be expected since the reflective measures have already been incorporated into the index. In this particular situation, an alternative might be to fit the AQI values into a model representing different types of health outcomes than those that were used to develop the index (i.e. emergency department visits and/or family physician visits).

An index should also be evaluated for its reliability, that is, its ability to consistently produce the same results under identical conditions[26, 84]. The best evidence for demonstrating an indicator's reliability is its successful previous use[67]. However, a newly developed indicator lacks a historical record of reliability. It is therefore suggested that if an indicator has a strong theoretical basis and if a retrospective analysis indicates that it would have informed us about an issue of concern, its reliability is provisionally established[67]. There are two broad types of reliability that are referred to in scale development literature. The first is internal consistency which represents how well the individual variable components of a scale reflect a common concept[72, 74]. The interpretation is if the variables have a strong relationship to the underlying concept they

will also have a strong relationship with each other. However, there are problems associated with the application of this reliability measure to index development. As it was already mentioned, the variable components in an index act as determinants of the index. This means that they each have a specific relationship to the index concept and may not contribute to the overall concept in the same way. Nunnally and Bernstein[92] declare that two variables that may be negatively related with each other can both serve as meaningful variable components to an index concept. Thus internal consistency is not an appropriate assessment of index reliability.

The second broad type of reliability measure mentioned in the scale development literature is test-retest reliability. Test-retest reliability reflects measurement consistency over time which identifies how well the scale correlates with itself across repeated administrations[74, 78]. However, the application of this reliability measure is usually in reference to data obtained from population groups that can be approached on different occasions to compare the consistency of their responses. When an index is developed using fixed physical data, it is impossible to make multiple comparisons since the data are not subject to change in the timeframe measured. This type of reliability measure can potentially be extrapolated for application to indices based on fixed information in terms of assessing the reliability of the methods used to obtain the variable component information. In cases where different methodologies exist to obtain the variable information, reliability of methods must be proven to continue with their use. A comparison can be made between the measurement methodologies used to determine the variable values to assess the reliability between different measurement methodologies.

Responsiveness

An index should also be assessed for responsiveness to variable changes. If an index is designed to detect variation in the state of conditions then it should be sensitive enough to detect these changes[68, 93]. Cairns[93] and Briggs[70] also clarify that this variability should not be associated with an all or none response, yet should be robust enough that it is not driven by minor differences in the source of the data used. Different source data can be used to test the behaviour of the index in detecting these variations. Krewski and Burnett[94] also state that good indicators should enable the detection of temporal and spatial trends and provide early warnings of potential problems related to the indicator issue being measured.

3.4.2 Considerations for Index Development

Since an index is supposed to serve as a communication tool, it also needs to be assessed for real-world application. The following factors should also be considered when constructing an index.

User considerations

Index development requires particular attention to the needs of the intended users. Some of these considerations are related to: user-assessment, transparency, complexity and public confidence. Although the users of the index should be identified during the clarification of the purpose of the index, there should be further investigation into the needs of these users to help guide the messaging development for the index. In a WHO report[70] on environmental health indicator development, it was stated that indicators should be readily understood and interpreted by the users. Thus, if possible the

complexity of the index should be kept to a minimum. At the same time an index should be recognizable and transparent so that the method of index formulation can be reproduced by others. This will lend confidence and credibility to an index when it is translated into application. Moreover, an index intended for public use such as an AQI needs to be associated with a high degree of public confidence. The index users need to have trust in the disseminators of the index information, for them to trust the index messages.

Messaging System

The messaging system forms a very important component to index development. It serves as the communication vehicle for the index to its intended users. The manner in which the index information is communicated can significantly influence how the index issue is perceived and what the subsequent responses will be[95, 96]. This is why different messaging schemes should be tested for message development. For an AQI, the AQI levels and descriptors really define how the AQI is communicated and need to be designed in such a way that makes the AQI both practical and user-friendly. Some of the considerations related to the messaging system of the index include education, accessibility, timing and individual tailoring. Providing a basic understanding of fundamental concepts of the underlying index issue is suggested for successful communication of an index[97-99]. Education will also result in an increased awareness for the significance of the index issue. Additionally, it is important to make sure that an index for public use is widely disseminated and easily accessible to all groups of society[71]. This is the only way that the public will benefit from the information available from the index. Moreover, decisions need to be made regarding the timing of the index

reporting (i.e. will the index be reported on a consistent schedule or will it only be reported when the index issue is believed to be most problematic?). Another consideration that has been mentioned in the application of AQIs is that the disseminated information should be individually tailored[100]. The level of air pollution affects different groups of people in different ways, based on a variety of factors such as health status, age, and exposure. Consequently, incorporating these differences into the messaging design of an index should be considered.

Uniformity

The AQI literature also suggests that an AQI should be applicable across time and space to support the use of the same index across a country[101, 102]. These criteria support the comparison of air pollution conditions as well as contribute to an increased understanding of the index. However, this can present a problem for countries with a large degree of variation in their monitoring capabilities and air pollution levels.

Feasibility

The overall feasibility of the proposed index also requires consideration. Resource and scientific constraints will greatly influence issues such as data availability, cost-effectiveness and time frame for development. These practical limitations also need to be considered when developing an index.

Associated Actions

The disseminators of the index information also need to consider if specific policy actions will accompany certain index levels. As previously mentioned, when air quality levels are categorized as "poor" certain immediate actions such as industrial closures or road closures could be implemented to reduce short-term air pollution.

Iterative Process

Finally, the process of index development needs to be dynamic and amenable to change with new advancements in the understanding of the index issue or index variable components. New developments can also be related to changes in the overall purpose of the index along with changes in data availability and levels of awareness and needs of the users[70]. This will ensure that the index remains valid and meaningful, and will also encourage those applying the index to rigorously reflect and evaluate their work.

3.4.3 Challenges

The area of index development and particularly environmental index development is still a developing one. As such, there are no clear guidelines towards index construction. Thus, those wanting to work towards developing an index need to review the associated literature of scale and indicator construction for guidance. One of the main challenges in developing an index is to simplify complex information without distorting the underlying truth[70]. This implies that there is a delicate balance between creating an easily understandable index and one that is still valid. Another difficulty arises when different kinds of variables need to be combined to formulate the index. The variables need to be transformed in a way that still captures their underlying significance towards the index measure. Further, data requirements can sometimes be so complex and extensive that they are not feasible within the resource constraints for index development. Those intending to work on index development need to be aware of these challenges and describe the limitations of their indices in relation to these factors.

3.5 Potential Limitations

Although an attempt was made to identify the relevant material for this review, there could have been additional references classified under different keywords that were not captured in the data extraction. Yet, based on the variety of sources and the commonality of the themes found, the review presents a general overview of the likely common conceptual, measurement and communication aspects of index and air quality development.

3.6 Conclusions and Suggestions

The great reliance of policymakers and the public on indices to obtain quick and easily understandable information on an issue of concern requires that indices are properly developed and evaluated. Through this review of the conceptual and measurement aspects of index development, the key steps towards index development were identified along with some of the important considerations for real-world application. Some of these index development steps and considerations can be used as index evaluation criteria since they represent factors for successful indices. Since one of the objectives of this thesis is to conduct a quantitative analytical comparison of various approaches towards AQI formulation, it is suggested that these criteria serve as the conceptual framework for informing an analysis into the properties of different AQIs.

4.0 A REVIEW OF AIR QUALITY INDEX FORMULATIONS

4.1 Summary of Objectives

The objective of this review is to identify the current state of knowledge and practices around the world relating to short-term air quality index formulation. This will help determine if a suitable index already exists for potential application towards an improved air quality index in Canada, and will help identify any general gaps and inconsistencies that may exist amongst different AQIs. This work satisfies one of the key steps of index development; *literature review*, identified in the previous section.

This review will begin with some background information on air quality indices. Then a review of AQI formulations described in the literature and in real world application will be presented. Finally, suggestions for potential AQIs to be evaluated in an analytical comparison will be provided.

4.2 Introduction

For over 30 years there has been an international recognition of the value of air quality indices in monitoring air pollution and informing policy makers and the public about air quality. Air quality indices have been described as the most successful types of environmental indices based on their prominence and public acceptance[76]. They have contributed to an increased understanding of air pollution problems and environmental issues as a whole.

Air quality index development and communication have been receiving increasing interest in recent years. This is connected with new developments in air quality health effects research and the increased accessibility of information through

web-communication. The negative health effects associated with air pollution are well known and through recent evidence it has been shown that these negative effects can occur at even low levels of air pollution with no observed thresholds. Consequently, the validity of incorporating prescribed limit values or standards has been questioned. In addition, it is stated that health effects are complicated from the additive or synergistic contribution of multiple pollutants[103], which is not generally accounted for in the majority of AQIs. Furthermore, with the technological advancements in our society, people can easily and quickly access information through the internet at any time[88]. This has increased the capacity and demand for up to date information relating to air quality conditions. As a result of these recent findings and changes, there has been an increased research effort to identify new methods of air quality index formulation and communication.

Air pollution is a global problem because of its ability to transcend borders. However, no uniformly accepted methodology for determining and reporting an air quality index exists. This stems from the many issues driving the development of AQIs, from scientific information concerning health and meteorology, to the political values of each country.

4.3 Methods

To identify references on air quality index formulation several search strategies were employed. Literature searches using Web of Science, Medline and the Environmental Sciences and Pollution Management databases were performed for all English citations from the earliest respective database coverage date to November 2003

that contained one of the following keywords: "air quality index", "air pollution index", "air quality indicator", "air pollution indicator " "air quality management", and "air pollution management". The University of Ottawa and University of Toronto library catalogues were also searched for English references containing one of the above keywords. The reference lists from all relevant references were also searched manually to find any further relevant references for inclusion in this review. The references obtained from these sources were examined and were included in this review if they reflected current air quality index formulations or proposed a theoretical model of AQI formulation.

4.4 Comparison of methods for AQI construction

There are a number of air quality indices that have been proposed in the literature and that are in real-world application. In 1978, Ott[63] presented a comprehensive review of AQIs in existence. In 2002, Garcia and Colosio[80] provided an international comparison of AQIs used in practice. The following review presents additional information on AQIs found in the academic literature and in real-world practice, and critically reviews the different methodologies.

The majority of AQIs are dominated by the aggregation of different pollutant sub-indices. This AQI structure has made it easy for countries to incorporate their ambient air quality guidelines or standards into an AQI formulation. A sub-index is usually calculated as the ratio of the observed pollutant concentration to its respective limit[63]. Then, the sub-indices are combined based on the choice of an aggregation function.

Aggregation functions are generally categorized into additive, multiplicative and maximum/minimum operator forms.

Additive

An example of an AQI employing an additive form of aggregation is the Oak Ridge Air Quality Index (ORAQI) developed by the Oak Ridge National Laboratory[63]. The ORAQI is based on 24-hour average concentrations of five air pollutants: CO, NO_2, O_3, TSP and SO_2. It employs an aggregation function where the different sub-indices are added, multiplied by a constant and then raised to a power of 1.37:

$$ORAQI = \left[5.7 \sum_{i=1}^{5} Ii \right]^{1.37}$$

where, I_i is equal to $(x/x_s)_i$ and I_i is the sub-index for each pollutant, x is the pollutant concentration and x_s is the pollutant air quality standard. The constants in the equation were selected so that the ORAQI would have a value of 10 when all pollutant concentrations were at their "naturally occurring or background level" and the ORAQI would be approximately 100 when all pollutant concentrations were equal to their air quality standard[63]. Thus, the constants are specific to the scenario where all five pollutant concentrations are available. Then, one of the limitations of the ORAQI is that it requires modification in cases where pollutant information is missing[64]. Chelani et al.[101] recently proposed the adoption of an ORAQI based AQI for the assessment of air quality in India. Because India does not yet have continuous and regular monitoring of air pollutants, they felt that an AQI based on single daily pollutant concentrations would be best, and cited the ORAQI as their basis. They evaluated the index by comparing index calculations of average annual air quality data to the observed data and found that the index calculations were consistent in declaring dangerous or poor air quality conditions based on pollutant

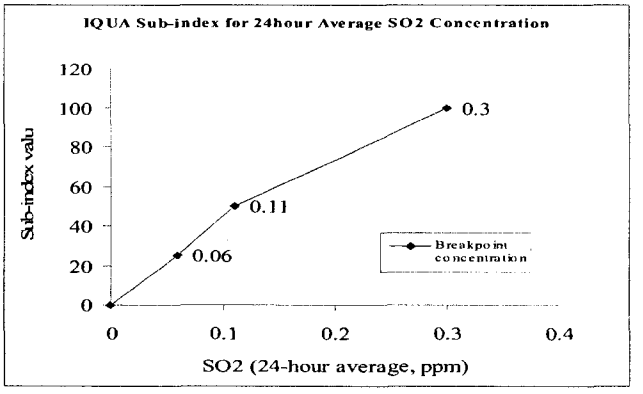
exceedances of air quality guidelines. They noted that similar comparisons could be done for daily data and indicated that the index presented a 'correct' picture of air quality. However, it has been noted that the ORAQI and other indices using this additive-power aggregation function are often subject to eclipsing (false negatives), declaring polluted air as less polluted[63] questioning the preceding conclusion that the index presents a 'correct' picture of air quality. This is because the ORAQI relies on more than one pollutant having high concentrations for the air quality to be considered 'high/poor'. Sengupta et al.[104] had previously evaluated the ORAQI for the Indian context, and reported that over 90 percent of the time there was an eclipsing problem, where the air quality was categorized as acceptable even when the air quality standard for some of the pollutants was exceeded. The ORAQI has also been criticized for being overly complex. Thomas[105] reported on the public acceptance of this index and found that there were concerns over the index being too difficult to explain to the public, compromising its public acceptance.

Maximum Operator

The maximum operator form of aggregation, overcomes some of the problems of eclipsing and complexity by reporting the maximum sub-index as the final index value. The majority of air quality indices used in practice are based on the maximum operator form of aggregation, where the maximum sub-index value is reported as the final index. In addition, most of the AQIs employing this aggregation method are based on the calculation of segmented linear functions for each sub-index that incorporate different limit values as breakpoints. A segmented linear function consists of two or more straight line segments, usually with different slopes, joined at successive breakpoints[63]. The idea

of using breakpoint values is common to the air pollution field, where governmental and international health authorities have defined air quality objectives or standards for air quality management and public health safety. The breakpoints are defined air pollutant concentrations. The intermediate values between the breakpoints are treated with a simple assumption; that adjacent breakpoints exist in a linear relationship. Each air pollutant is associated with its own segmented linear function, where breakpoint levels are matched to a particular sub-index value. Using this function it is then possible to input any concentration and obtain a corresponding sub-index value (See Figure 1 for an example of the segmented linear function).

Figure 1. Segmented linear function: IQUA Sub-index for 24-hour average SO_2 concentration.



* From Guidelines for the IQUA, Federal-Provincial Advisory Committee on Air Quality (1992)[106]

The maximum operator form of AQI formulation builds on the segmented linear function methodology by taking on the largest value of any of the sub-indices. The basic assumption is that the index treats all pollutants equally with respect to the quality of the air at the breakpoint levels. This is the methodology currently used in the majority of countries including the AQI of the U.S. EPA and the IQUA in Canada. Thom and Ott[63] have proposed a general version of this type of index called the Uniform International

Pollution Index (UNIPEX). Each UNIPEX sub-index uses two breakpoints that have a scientific basis, a short term standard (UNIPEX=100) and a level reflecting significant harm to health (UNIPEX=500). The scale is then divided into four equal segments with the concentrations of the other breakpoints determined from the linear relationship of the two given breakpoints. Khordagui and Al-Ajmi[83] presented the results of an adapted UNIPEX for Kuwait. They found that the index was able to reflect the day-to-day variations in ambient air quality and was easily understandable.

The maximum operator form of aggregation offers some benefits in its ease of understanding and greater accuracy in categorizing air quality conditions with the requirement that only one pollutant concentration be considered as 'poor' for air quality conditions to be declared as 'poor'. However, there are also certain limitations to this aggregation form. Since the pollutant with the maximum value drives the final index, the information associated with the rest of the pollutants is lost. Thus, other pollutants that are high or relatively high are not reported which may have important implications for those particularly sensitive to specific pollutants. Additionally, the maximum operator function does not account for the additive or synergistic contribution of multiple pollutants. Moreover, it is not suitable for the comparison of regions and changes over time, because different environmental situations can result in the same final index value. It only provides information relating to one single pollutant where in some cases all may be relatively high[86, 90, 107]. Further, this aggregation form assigns the same relative importance to each pollutant, which may not necessarily be true for the associated air conditions and health outcomes.

Standardized Additive

A few countries have chosen an alternative to the maximum operator for variable aggregation in their AQIs. Germany and Slovakia have developed indices that use the addition of each pollutant sub-index to produce a final index value, to account for the additive contribution of multiple pollutants[80, 102]. This can be seen as a more precautionary approach for air quality assessment but is associated with problems of ambiguity where air pollution levels become exaggerated. Stone[102] notes, that unless the predicted health effects occur, a loss in confidence and credibility will occur; that in turn can cause the AQI to become a meaningless information tool for the public. In the Czech Republic and Naples, Italy, a standardized additive aggregation form is used[80]. This index is similar to the one described above but is standardized by dividing by the number of pollutants. Garcia and Colosio[80] note that with this standardization, the extremes due to certain pollutants are averaged out, resulting in eclipsity.

New Pollutant Index

The New Pollutant Index (NPI) introduced by Malakos and Wong[108], was developed to improve upon some of the shortcomings in the U.S. Pollutant Standards Index (PSI). They proposed the inclusion of multiple pollutants to account for the synergistic effects of pollutant combinations. Their NPI was based on the factor of safety concept that incorporates a margin of error to systems that are unpredictable or not thoroughly understood[108]. They argued that the factor of safety inherently built into the PSI through the use of air quality standards, was not sufficient to account for pollutant interactions. They used a modified version of the pollutant index developed by Green et al.[109] named the Florida Interdisciplinary Center for Aeronomy and other Atmospheric

Sciences (ICAAS) Air Quality Index because of its flexibility in incorporating synergistic effects. The application of the factor of safety concept requires that an allowable "load" first be defined. The U.S. National Ambient Air Quality Standards (NAAQS) were used to determine the load limit concentrations (C^*). Their new index is defined below and incorporates the five criteria pollutants of the PSI as well as a scaling factor (S_i) represented by the National Ambient Air Quality Standards (NAAQS).

$$NPI = I_{ICAAS}(C_1, C_2, C_3, C_4, C_5) / I_{ICAAS}(C_1^*, C_2^*, C_3^*, C_4^*, C_5^*) \times 100$$

where,

$$I_{ICAAS} = \left[\sum_{i=1}^{n}\left[(C_i/S_i)^2 + b_{i,j}(C_i/S_i)\,(C_j/S_j)\right]\right]^{1/2}$$

and i represents a criteria pollutant, C_i is the measured concentrations, C_i^* is the load limit concentration for each pollutant (the air quality standard), S_i is the scale factor representing the pollutant specific NAAQS, $b_{i,j}$ is the interaction constant representing the synergistic effect and j represents a secondary criteria pollutant. The authors assumed that the interaction constant ($b_{i,j}$) of 1.5 would account for the interaction between SO_2 and PM_{10} since Green et al. [109] had originally used this constant to define the synergism between SO_2 and TSP. However, they did recommend that further research be required to better understand the interactions between pollutant as well as further verification of the scaling factors (i.e. NAAQS). Furthermore, the authors recommended that the NPI would require long-term testing before its adoption. This could be achieved by comparing air ratings given by the index with documented complaints of respiratory and other ailments associated with criteria pollutants.

Root Sum Exponential

Swamee and Tyagi[85] have developed a multiple pollutant AQI model to show a more composite picture of air pollution. They presented an AQI model where air pollution sub-indices are aggregated using what they describe as "an ambiguity and eclipsity-free variable weight function". In their proposed formulation, sub-indices are also represented by the pollutant concentration over a defined standard concentration, but have proposed a different function for aggregation. Their proposed aggregation form is presented below and is in the form of a root sum exponential:

$$I = \left(\sum_{i=1}^{n} si^{1/p}\right)^{p}$$

where I is the aggregate index, n is the number of sub-indices, si is the sub-index and p is the exponent constant. They conceived that a 'p' value would exist where the aggregation included the effect of all the sub-indices and the ambiguity was minimized (i.e. less polluted air would not be classified as polluted). The si (sub-index for each pollutant is determined by:

$$si = s_s (q/q_s)^m$$

where s_s is the scaling coefficient, q is the pollutant concentration, q_s is the standard pollutant concentration and m represents a sub-index constant. They found that this was achieved with p=0.4. Further, since the formulation incorporated the results of all pollutant sub-indices, eclipsity/false negative classifications would also be minimized. Although they reported that extensive study was undertaken to determine the value of 'p', the exact process through which this was determined was not described. Thus, this AQI formulation is accompanied by a lack of transparency in the choice of 'p' and there is

complexity in the determination of 'm'. In addition, Bruno and Cocchi[88] have criticized this approach for its lack of relative weighting among the different pollutants.

Revised Air Quality Index

Recently, Cheng et al.[86] reported on a revised air quality index (RAQI) that incorporates the five key air pollutants and local air quality conditions. It combines the original framework of the U.S. PSI with background air pollution information and a measure of uncertainty represented by Shannon's entropy function. The formulation is described below and can be broken down into three separate factors. The first factor is the maximum operator function, where the maximum value of each pollutant sub-index is determined. The second factor brings in information on the background air pollution for a region. The numerator of this second factor is determined by calculating a daily average of the different pollutant sub-indices and then summing all of these values. The Ave_{annual} term in the denominator indicates that the average over the entire year for the quantity inside the brackets is to be calculated. Thus, in this case the denominator represents the overall mean of all daily averages. The third factor is a function representing the uncertainty measure by incorporating Shannon's entropy function. The numerator represents the annual average of the daily entropy calculations (i.e. the yearly average for the daily uncertainty associated with an index value). The denominator is a function representing the daily uncertainty with the index value.

$$RAQI = Max[I_1,I_2,\ldots,I_5] \left(\sum_{j=1}^{5} Ave_{daily}[I_j] \Big/ Ave_{annual}\left[\sum_{j=1}^{5} Ave_{daily}[I_j] \right] \right)$$

$$\times Ave_{annual}\{Entropy_{daily}[Max[I_1,I_2,\ldots,I_5]]\} \Big/ Entropy_{daily}[Max[I_1,I_2,\ldots,I_5]]$$

Air quality data were used from the Kaoping region of Taiwan to compare the RAQI and the PSI. It was found that the RAQI exhibited a wider range in AQI values during days with high air quality index values. This was explained by the fact that the PSI only considers the maximum sub-index whereas the RAQI incorporates information from the five pollutants as described above in the second and third factors. However, the authors stated that this was accompanied with an exaggeration of high pollution episodes. As a result, the authors recommended that the RAQI might be better suited for reporting air quality in the long-term rather than the short-term.

Hierarchical Aggregation

Another form of air quality index aggregation that has been proposed in the literature is hierarchical aggregation. Barbiroli et al.[107] presented an air quality index that is obtained through the construction of intermediate indices of various levels. A hierarchical tree structure is used where each index of a particular level is obtained by the aggregation of two or more indices at a lower level. Through this method of aggregation, the index can be individually tailored to site specific criteria and adapted to the monitoring capacities of each area. They recommended using the arithmetic mean as the aggregation function for the individual indices when the function of the index is to evaluate resources, but thought that the maximum operator form was best suited for an AQI designed to inform the public. Bruno and Cocchi[88] proposed a class of AQIs that are designed to be able to compare situations across time, space and pollutants. The final index is based on the U.S. PSI but is constructed by hierarchical aggregations of these three dimensions. This process allows one to combine the results of several monitoring stations to achieve better overall representation of air quality in a certain area. They also

proposed incorporating a measure of variability with every index. Measures of dispersion do offer important information; however communicating their meaning to the public is difficult. The proposed method offers some insight for spatial referencing and site specific tailoring; however it is associated with great complexity and its functionality as a public information tool is uncertain.

Fuzzy Set Theory

To address some of the concerns over the use of standards and guidelines in the assessment of air quality, Fisher [110] proposed the use of fuzzy set theory to guide development. Fuzzy sets include fuzzy numbers and probability functions encompassing a range of values. A fuzzy number describes a quantity that lies within two limits, but has one typical value[110]. This avoids the use of sharp boundaries, which declare air pollution as acceptable or unacceptable depending on which side of the boundary the reading lies.

Health Risk Based Indices

To further account for the uncertainty surrounding prescribed standards and the evidence of a no threshold effect of different air pollutants, several recommendations for constructing an AQI that incorporates health risks and dose-response relationships have been offered. In 1978 Ott[63] stated that an air quality index could be developed using damage functions that reflected the adverse health outcomes of air pollution. At the time, there was no desirable method for translating observed air pollutant concentrations into estimated health risks. In 2000, Khanna[90] developed an air pollution index (API) based on epidemiological dose-response functions associated with each air pollutant and the consequent welfare losses. Some of the welfare losses due to air pollution include

productivity losses from days missed from work and increased economic burdens to the health care system. The formulation combines information from ambient concentrations of all pollutants. The use of welfare losses provides a common metric in which the ambient concentrations of different pollutants can be aggregated. Khanna used information from the U.S. EPA relating to public health impacts and welfare impacts of short-term air pollution exposure, to develop a new AQI. In an analytical comparison between the PSI and the proposed API two significant differences were noted. First, the API facilitated a detailed ranking of regions by air quality since information from all relevant pollutants was incorporated into the index. Second, the API produced some results that were in contradiction to the PSI. This was explained by the fact that the PSI is determined by a single pollutant with the highest relative concentration, whereas the API incorporates concentrations of all pollutants. Thus, if all pollutants are relatively high, poorer air quality conditions could be declared with the API. Some of the recommendations for future research included the incorporation of weights for each of the indicators based on the relative damage and probability of damage, and location specific studies on willingness to pay as a method to assign the welfare weights.

In Srivastava and Kumar's[111] economic valuation of health impacts due to air pollution in India, an AQI for respiratory diseases was presented. The AQI formulation was an additive aggregation of air pollutant concentrations with specific pollutant weights. The weights were obtained from Sterling et al.'s[112] 1967 study on urban hospital morbidity and air pollution. They described the weights as a function of the pollutant's ability to cause respiratory symptoms and that the ability of the pollutant to cause disease symptoms would not alter with location. The changes in pollutant

concentrations would consequently drive changes in the AQI. They applied AQI information to obtain an estimate for daily exposure and then used the logit model to estimate the probability of different health outcomes. This information was then used to estimate the economic losses associated with the predicted health outcomes. However, it was not clear which AQI was applied to the estimation of daily pollutant exposure and the reasons for their decision.

Stieb et al. [113] and Cairncross and John [114] recently proposed an alternative formulation for an AQI in light of the deficiencies associated with existing air quality indices. Their proposed AQI formulations are based on health risk estimates from population-based epidemiological studies of air pollution and health. This approach combines the observed association between each individual pollutant exposure and health outcome, to determine the public health impact of these exposures. Thus, each observed pollutant concentration is weighted by its associated relative risk for the health outcome and contributes to a combined risk estimate of air pollution. This quantification is translated into an index value used to describe the overall quality of the air. Further detail on the Stieb et al.[113] approach is presented in section five of this thesis.

This approach seeks to address some of the shortcomings identified with standard driven indices by providing a strong health base to the index, incorporating the most recent air pollution health science and a multiple pollutant approach.

Exposure Concepts

A different approach towards AQI construction involves the use of exposure concepts. Smith[100] stated that it is not air quality that drives adverse health effects but exposure quality, and thus advocated that AQI construction should include measures of

exposure. Exposure quality refers to factors such as the location and timing of source emissions with respect to the places that people spend their time. Because of the inherent difficulties in measuring exposure itself, he recommended using exposure effectiveness. Exposure effectiveness is defined as "the fraction of released material that actually enters someone's breathing zone as measured in exposure units"[115]. By combining ambient monitoring with exposure measures it was felt that a more comprehensive picture of air pollution health risk could be achieved. However, this method would call for extensive coverage of information relating to different exposure circumstances such as indoor air, domestic activities, occupational exposures and different health effects for different population groups, and thus may not be a practical alternative.

4.5 Discussion

The majority of AQIs incorporate the use of standards or guidelines into their formulation. One of the main advantages associated with standard driven indices is that they are benchmarked and thus capable of conveying clear messages about policy performance[76]. However, there are several important disadvantages with these types of indices. A limit value in terms of a fixed concentration, does not in reality distinguish between acceptable and non-acceptable conditions. There is considerable uncertainty in defining where a limit value should lie[110]. This can be seen by the diversity in standards associated with the same pollutant for different countries. As well, recent health science research has shown that harmful health effects occur at levels below prescribed standards with no observable threshold that distinguishes between the occurrences of effects. Recognizing this, the WHO recommended against a specific guideline value for

particulate matter[103]. Instead they provide risk estimates associated with PM concentrations. Furthermore, ambient air quality levels have decreased in most developed countries, where present standards are rarely exceeded[116]. However, observable health effects related to air pollution still occur, calling into question the validity of relying on standards. In recognition of the problems associated with standard-driven indices, several alternate proposed options have been identified in the literature. The following table provides a summary of the advantages and disadvantages associated with the different methods of AQI construction.

Table 1. Advantages and Disadvantages of Different Methods of AQI Formulation

AQI Formulation	Advantages	Disadvantages
Standards Based Indices		
Additive	- incorporates multiple pollutants - reflects additive contribution of pollutants - use of standards provides benchmarks	- does not reflect current health evidence resulting in frequent false negatives - requires data availability of all pollutants - shown to have low public acceptance - complexity
Standardized Additive	- incorporates multiple pollutants - reflects additive contribution of pollutants - use of standards provides benchmarks	- does not reflect current health evidence resulting in false positives and negatives - requires data availability of all pollutants - complexity
Maximum Operator	- common international approach - reduced potential for false positives - use of standards provides benchmarks - does not require data availability of all pollutants - good public acceptance	- does not reflect current health evidence and is thus associated with false negatives - represents only a singular pollutant - does not reflect multiple pollutant contributions - unable to make comparisons
New Pollutant Index	- incorporates multiple pollutants - reflects synergistic and additive contribution - use of standards provides benchmarks	- pollutant interaction term needs further development - needs greater evaluation - does not reflect current health evidence and would thus be associated with false negatives

AQI Formulation	Advantages	Disadvantages
Root Sum Exponential	- incorporates multiple pollutants - reflects additive contribution of pollutants - use of standards provides benchmarks - extensive analytical comparisons completed for final formulation development	- obscure in choice of constants - requires data availability of all pollutants - associated with false negatives because does not reflect current health evidence
Revised Air Quality Index	- incorporates multiple pollutants - incorporates uncertainty measure and background air pollutant concentrations - use of standards provides benchmarks	- complex - does not reflect current health evidence resulting in false positives and negatives - not suited for short-term air quality reporting
Hierarchical Aggregation	- individually tailored to site criteria and data availability - better overall representation through combination of multiple information - incorporates measure of variability - use of standards provides benchmarks	- complex - may not be feasible - does not reflect current health evidence - max. operator recommended as final aggregation method which has a number of limitations
Health Risk Based Indices		
Khanna's formulation	- relies on health risk information - incorporates multiple pollutants - allows for comparisons	- data requirements may not be available - complex aggregation function - formulation not finalized
Srivastava and Kumar formulation	- relies on health risk information - incorporates multiple pollutants - allows for comparisons	- not transparent - conceptual basis/rationale lacking
Stieb et al. *and* Cairncross and John formulations	- relies on health risk information - incorporates multiple pollutants - reflects current health evidence from epidemiological studies - reflects additive contribution of pollutants - allows for comparisons - transparent - extensive analytical comparisons completed for final formulation development - reduced potential for false negatives and positives because of evidence base	- health risk functions subject to change depending on data - final formulations not finalized
Other Indices/Approaches		
Fuzzy Set Theory	- relies on a range of values to act as 'standards' rather than distinct cut points	- complex - still requires a decision to be made with regards to safety range - does not reflect current health evidence - no formulation currently available
Exposure Concept	- provides comprehensive picture of air pollution health risk - focus on individual tailoring	- requires extensive amounts of information, thus not feasible - needs greater evaluation - comparability is compromised

4.6 Potential Limitations

In this review of AQI formulations there could have been additional references classified under different keywords that were not captured in the data extraction. However, it is suspected that most of these references would have been classified under one of the keywords so that similar references could be retrieved. Likewise, from the variety of methodologies identified for AQI formulation a diverse array of options is presented for AQI formulation consideration.

4.7 Conclusions and Suggestions

Through this review of the literature and current practices related to short-term air quality indices, several AQI formulations were identified and qualitatively assessed for their strengths and weaknesses. Based on this assessment the following formulations are likely not feasible for real-world application because of their complexity, resource requirements, and analytical uncertainties: New Pollutant Index, Revised Air Quality Index, Hierarchical Aggregation, Khanna, Fuzzy Set Theory, Srivastava and Kumar, and Exposure Concept Indices. The Additive and Standardized Additive indices also suffer from the significant problems of ambiguity and eclipsity and are thus not suggested as options. The remaining AQI formulations options: Maximum Operator, Root Sum Exponential by Swamee and Tyagi[85], and Health Risk Based Index are associated with some disadvantages but represent feasible options with fewer analytical gaps. These three index options are recommended for the analytical comparison of AQI formulations in section six of this thesis.

In terms of the specific mathematical formulations that should be used for the analytical comparison, the choice of formulations needs to be based on index options that represent real options for an improved Canadian AQI based on analytical understanding and feasibility. One of the key factors should be that the AQI includes $PM_{2.5}$, to reflect the current scientific evidence of the health risks associated with this pollutant. As such, the IQUA for Canada is not recommended for the analytical comparison because it fails to include $PM_{2.5}$. It is suggested that the U.S. PSI and the Ontario AQI are included in the analytical comparison as the Maximum Operator index options. These AQIs are currently in existence and reflect recently updated attempts at AQI development. The Stieb et al.[117] health risk based AQI formulation is also recommended for inclusion in the analytical comparison since it has been developed for use in Canada incorporating recent Canadian air quality health risk evidence. It is proposed that the Root Sum Exponential formulation by Swamee and Tyagi[85] be adapted for evaluation in the analytical comparison by incorporating several different types of updated *standards* into the general formulation. However, it is suggested that only qualitative interpretations are made using the Swamee and Tyagi formulations since it will not be possible to assign values to all the necessary variables. Assignment of the sub-index constant 'm' requires additional analytical investigation which is beyond the scope of the thesis.

5.0 OVERVIEW OF THE HEALTH-RISK BASED AIR QUALITY INDEX

An overview of the health risk based AQI formulation is presented since the detailed methodology and groundwork for this formulation is reflective of the process of developing a new index formulation as described in the earlier reviews. The other formulations examined in the analytical comparison were already in use or had undergone some preliminary testing by their respective authors. This overview provides the opportunity to apply some of the theoretical steps for index development into practice.

5.1 Defining the Purpose

The first step in describing the health risk based index (HRBI) is to define its purpose. The HRBI is defined as a communication tool dealing with short-term changes in air pollution concentrations. The primary objective being to provide air quality information to the public that will enable them to take appropriate actions to protect themselves from the adverse health effects of air pollution. A secondary objective is to increase awareness of the burden of illness attributable to air pollution at current levels of exposure. The latter is a means of motivating changes in both individual behavior and public policy, which may ultimately lead to reductions in emissions of air pollutants from anthropogenic sources, and resulting improvements in public health[118].

The AQI Management Committee specifically declared the importance of health science in informing and guiding the development process. This is reflected in their declaration that the AQI would be the best available indicator of current and forecasted levels of health risk attributable to common air pollutants. To support this vision the AQI

Management Committee recommended that the AQI should be based on up to date scientific knowledge of the relationship between pollutant levels and health impacts[119]. The HRBI has been designed as a national Canadian AQI to be used throughout the country for public health communication. It is intended to offer a more accurate representation of the health risk due to air pollution than the current Canadian AQIs in existence.

5.2 Literature Review

A literature review of existing indices was undertaken and has been summarized in section four of this thesis. This review facilitated a qualitative assessment of different approaches towards AQI formulation and helped guide the choice of indices to be evaluated in the analytical comparison.

5.3 Conceptual Basis

The background information that has been provided in the introductory section of this thesis forms a large part of the conceptual basis for the new HRBI. The variable components have been identified as the 'criteria' air pollutants and evidence of a no-threshold level of health risk as well as the additive contributions of multiple pollutants to health risk have been described.

5.4 Variable Selection & Aggregation

Variable selection and aggregation are jointly discussed as they were undertaken concurrently in the HRBI development process. This section provides significant detail

underlying the HRBI formulation including some of the analysis that was undertaken to arrive at the final variable selections and aggregation formulations.

As previously described in Section 4 of this thesis, the proposed HRBI formulations are based on health risk estimates from population based studies of air pollution and health. Each observed pollutant concentration is weighted by an associated relative risk and contributes to a combined risk estimate of air pollution. To construct the HRBI formulations, a percent increase in mortality relative to zero concentration of each pollutant was initially calculated for a reference period. This was carried out by exponentiating the product of each pollutant's coefficient and the measured concentration of that pollutant on a specific day, subtracting 1, multiplying by 100, and then summing across all pollutants. This percent was then averaged across all available cities for each day, weighted by the average number of deaths per day by city, during this period. Weighting in proportion to the frequency of each outcome per day was done to avoid undue weighting to small cities with high levels of pollution and to achieve the most accurate assessment of public health impacts in absolute terms[113]. This is summarized in equation 1.

$$\text{Mortality weighted percent excess deaths} = \sum_{j=1\ldots n}\left[\left(m_j / \sum_{j=1\ldots n} m_j\right)\sum_{i=1\ldots m} 100\left(e^{B_i x_{ij}} - 1\right)\right] \quad (1)$$

where, B_i is the regression coefficient from a Poisson model linking the i^{th} air pollutant with mortality, x_{ij} is the concentration of the i^{th} pollutant in the j^{th} city on the t^{th} day (for cities 1 to n and pollutants 1 to p) and m_j is the daily average number of deaths in the j^{th} city.

For the purposes of creating a numerically simple scale from 0-10, all values were scaled back by multiplying each value by 10 and dividing by the maximum value (equation 2).

$$c = \max_{t=1\ldots p}\left\{\sum_{j=1\ldots n}\left[\left(m_j / \sum_{j=1\ldots n} m_j\right)\sum_{i=1\ldots m} 100\left(e^{B_i x_{ijt}} - 1\right)\right]\right\} \quad (2)$$

Then the index value for any other day in any city could be calculated by simply inputting the pollutant concentration information (equation 3). This results in an unbounded index on a 0 to 10+ scale.

$$\mathbf{AQI} = (10/c)\sum_{i=1\ldots m} 100\left(e^{B_i x_i} - 1\right) \quad (3)$$

where, B_i is the regression coefficient from same Poisson model linking the i^{th} air pollutant with mortality as in (1), x_i is the concentration of the i^{th} pollutant and c is the scaling factor from step 2.

5.4.1 Source of Regression Coefficients for HRBI

The original HRBI formulation presented by Stieb et al.[113] was based on the observed multi-pollutant, no-threshold association between particulate and gaseous pollutants, and mortality in a daily time-series study of 8 Canadian cities[120]. However, subsequent to the development of this formulation, it was revealed that the computer program implementation of the generalized additive model analytical approach used in this and other daily time-series studies was flawed [27, 28]. This necessitated a re-analysis of the primary data using robust statistical approaches, and a reformulation of the index based on these new analyses. Burnett et al. conducted a new analysis of air pollution and mortality in 12 Canadian cities[121], the results of which were found to be broadly similar to the earlier findings. In the interest of generating results which were more directly

relevant to current exposure levels and mixes, and which utilized continuous particulate matter measurements, a similar analysis was conducted for the period 1998-2000 for 11 cities[113]. As an additional feature, both mortality and cardiovascular and respiratory hospital admissions were examined as a means of evaluating whether they would lead to consistent index formulations. The Burnett study was based on the longest available time-series of Canadian data, from 1981-1999 and provided mortality risk estimates for all measured pollutants. The Stieb study used more recent exposure and outcome information (1998-2000). In both studies, natural spline functions were employed to adjust for temporal trends and for the effects of weather on the health outcome. Natural splines are not affected by the statistical problems associated with the use of non-parametric smoothers in generalized additive models[50]. Results from single pollutant models were employed because of the problems associated with the interpretation of conventional multi pollutant models. Because only the joint risk among pollutants is captured in this index formulation, i.e. attribution is not made to individual pollutants; double counting of risk among correlated pollutants is not a concern.

The health risk estimates for mortality were used in the construction of the proposed health risk based formulations. While the Stieb et al.[113] study also examined the association of cardiovascular and respiratory hospital admissions with air pollution; these health risk estimates were less stable than the results for mortality. At this stage it was considered premature to include the hospital admission results, and more consideration was needed on how different health outcome risk estimates would be combined in an AQI formulation. The inclusion of these 'other' health outcomes is still

being investigated and as additional analysis is completed the results will likely be evaluated for incorporation into the new HRBI in the future.

The use of health risk estimates from a worldwide meta-analysis (MA) of air pollution and mortality[42] was employed as a sensitivity analysis. However, it was decided that Canadian studies of air pollution and health risk were most relevant for the purposes of creating an AQI for the Canadian context. Health risk estimates from these studies would be most representative of exposure levels, exposure mixes, and population characteristics in Canadian cities. While it could be argued that city-specific data would be even more relevant to each city and that city specific AQIs should be constructed, it has been observed that multi-city health risk estimates provide more stability and precision[122]. Furthermore, a uniform national Canadian AQI would allow for between city comparisons and promote uniformity in air monitoring practices across the country.

The risk estimates for the five key pollutants from the two Canadian studies and the worldwide meta-analysis are presented in Table 2. All concentrations are daily averages, except for O_3, which is a daily 8-hour maximum. The O_3 concentrations for the Burnett study and the meta-analysis were originally reported based on daily maximum values. For comparison purposes they have been adjusted to daily 8-hour maximum concentrations. The ratio of the mean concentration of the ozone daily 8-hour maximum and the mean concentration of the ozone daily maximum for the period 1998-2000 was calculated for rescaling. The risk estimates selected were based on year round information so that the index could justifiably be applied year round. The risk estimates from the three sources exhibited similarities in terms of the relative effect amongst pollutants. However, the effect of NO_2 from the meta-analysis was considerably smaller

and that of $PM_{2.5}$ from Stieb et al. was somewhat higher. The effect of ozone in the Burnett study was also higher than the other two sources. The CO effect from the meta-analysis was approximately six fold higher than in either of the Canadian studies. This estimate was based on the fewest primary studies (4) of all the pollutants considered in the meta-analysis.

Table 2. Percent increase in mortality at mean pollutant concentrations

Pollutant	Mean conc'n [a]	Burnett	Stieb	Meta-Analysis
NO_2	18.8	1.88	1.60	0.78
O_3	28.2	2.97	1.03	1.49
SO_2	4.6	0.34	0.72	0.44
$PM_{2.5}$	8.2	0.49	0.94	0.34[b]
CO	0.7	0.47	0.56	2.97

[a] units are ppb for NO_2, O_3 and SO_2, ppm for CO and ug/m^3 for PM
[b] Percent increase is for PM_{10} not $PM_{2.5}$

5.4.2 Description of the data

The process of development for the new HRBI involved a series of sensitivity analyses that will be described later relying on a common dataset for evaluation. Air pollution data were obtained from the Canadian National Air Pollution Surveillance (NAPS) network. The NAPS network is a cooperative program of the federal, provincial, territorial and some regional governments to monitor and assess the quality of the ambient air throughout Canada. Since its establishment in 1969, the air quality data gathered by NAPS has been used for the evaluation of air pollution control strategies, identifying urban air quality trends and providing warning of emerging air pollution issues. In addition, one of the key objectives of NAPS was and continues to be the support of real-time reporting of air quality information to the public. Currently the NAPS network collects continuous air quality data for SO_2, CO, NO_2, O_3, TSP, PM_{10} and

$PM_{2.5}$ in over 175 communities in Canada[123]. This allows for a common national monitoring and reporting framework.

CO, NO_2, O_3 and SO_2 are measured using reference methods, methods of sampling and analyzing air pollutants that use U.S. EPA designated instruments. CO is measured using non-dispersive infrared spectrometry, NO_2 using chemiluminescence, O_3 using chemiluminescence/ultraviolet photometry and SO_2 using coulometry/ultraviolet fluorescence. Continuous $PM_{2.5}$ and PM_{10} measurements are made using tapered element oscillating microbalance (TEOM) instruments [113].

The NAPS data used in the process for HRBI development consisted of daily averages for all pollutants except ozone, for which the daily 8-hour maximum was used since this is the commonly reported metric for ozone reporting and air quality epidemiological studies. Thus, each day consisted of one set of corresponding air pollution values. Daily averages and O_3 8-hour maximums were chosen as the air pollution measures, to provide a correspondence between the source regression coefficients and to maintain nationally consistent measures.

5.4.2.1 Data Considerations

With the recent scientific advancements revealing the important human health effects of acute exposure to $PM_{2.5}$, access to continuous $PM_{2.5}$ data dictated the year selection of the dataset to be used. Although national PM data have been available since 1984, continuous $PM_{2.5}$ monitoring only began in 1994 across some sites [3, 124]. At the time of HRBI development, access to NAPS data was limited to the year 2000.

The selection of data years and Canadian cities was determined by the availability of the five key pollutants. Although cities from all provinces and territories are not represented, the cities included in the final dataset are large Metropolitan cities that extend across the country and represent the majority of living space for Canadians, translating into the major locations of air pollution exposure. The cities included in the final dataset were: Calgary, Edmonton, Hamilton, Montreal, Ottawa-Hull, Quebec city, Saint-John, Toronto, Windsor and Vancouver for the data years 1998 to 2000.

5.4.2.2 Handling of Missing Data

In the NAPS dataset: Missing data in the modified NAPS dataset are attributed to several technical issues that arise with normal monitoring practices of outdoor air pollutants. The physical monitoring station could have experienced technical difficulties or may have undergone a move to a new site. In these cases of missing pollutant data, there is no imputation. The information for that day is recorded as missing.

In the analysis: For each individual city, days where one of the five key pollutants was missing were excluded from the analysis. The full suite of daily pollutant information was required to assess the contribution and influence of each pollutant to the final AQI value for each day, and to obtain a comprehensive picture of the various AQI formulations.

5.4.3 HRBI Application to Canadian Cities and Recent Data

5.4.3.1 Analysis of Missing Data

The total number of days across all cities, where all five key pollutants were available for the 10 cities was 9128. Table 3 summarizes the total number of days where full pollutant information was available for each city. For the three-year study period, Toronto and Montreal had the most comprehensive pollutant data whereas Saint John and Windsor had the least with approximately half the number of days missing.

Table 3. Number (percent) of days where 5 key pollutants were available for each city, NAPS 1998-2000

City	Number of days (percent)
Calgary	1069 (97.5)
Edmonton	979 (89.3)
Hamilton	1062 (96.9)
Montreal	1093 (99.7)
Ottawa	1076 (98.2)
Quebec	796 (72.6)
Saint John	614 (56.0)
Toronto	1096 (100)
Vancouver	717 (65.4)
Windsor	626 (57.1)
TOTAL	9128

5.4.3.2 Comparison of HRBI using different Source Regression Coefficients

The distribution of HRBI values for the different source regression coefficients and for different numbers of pollutants was determined using the NAPS dataset from 1998-2000, for 10 Canadian cities. The distribution of values represents 1096 days, a weighted average of the 9128 days. It was important to examine HRBI formulations with varying numbers of pollutants to investigate the contribution of certain key pollutants and to satisfy the directives provided by the AQI Management Committee for an assessment

of a 2 pollutant formulation with only O_3 and $PM_{2.5}$. Thus, when reference is made to the 5-pollutant, 4-pollutant, 3-pollutant or 2-pollutant models, they are to be known as follows:

Table 4. Description of Pollutant Models

Pollutant Model	Included Pollutants
5-pollutant	O_3, $PM_{2.5}$, NO_2, SO_2, CO
4-pollutant	O_3, $PM_{2.5}$, NO_2, SO_2
3-pollutant	O_3, $PM_{2.5}$, NO_2
2-pollutant	O_3, $PM_{2.5}$

Figures 2a to 2l present bar charts of the percent distribution of AQI values for the different AQI formulations and Table 5 summarizes the percent frequency of days at each AQI level for the different formulations. All of the models using the Burnett study risk estimates classify the majority of days at AQI levels of >3 to ≤6. The results of the 3-, 4- and 5-pollutant models are very similar in their distribution of days between 0 to ≤3, >3 to ≤6 and >6 to ≤10. However, the 2-pollutant model tends to have more days at a lower AQI level.

Using the risk estimates from Stieb et al., similar distributions were found, with the majority of days dispersed at the >3 to ≤6 AQI level. Those HRBI formulations using the risk coefficients from the worldwide meta-analysis also have the majority of days spread across the >3 to ≤6 AQI range. However, there are a greater percentage of days at higher AQI levels as compared to the other formulations. This may result from the comparatively lower coefficient for NO_2, which results in a lower maximum index value being applied as a scaling factor, thus inflating index values in general. In examination of the different pollutant combinations, the elimination of CO and SO_2 appear to have

little effect on the overall AQI distributions. In contrast, when NO_2 is eliminated the observed distributions experience a notable shift.

Figure 2a. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2, SO_2, CO

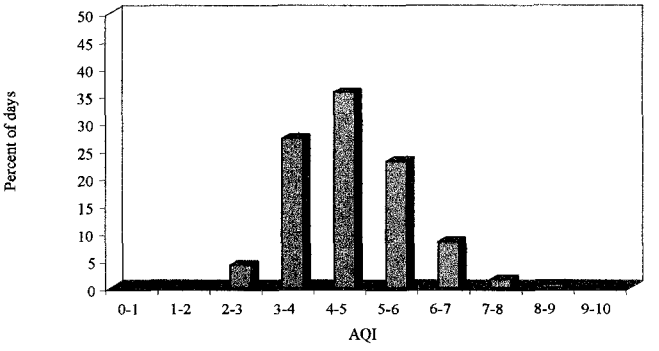


Figure 2b. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2, SO_2

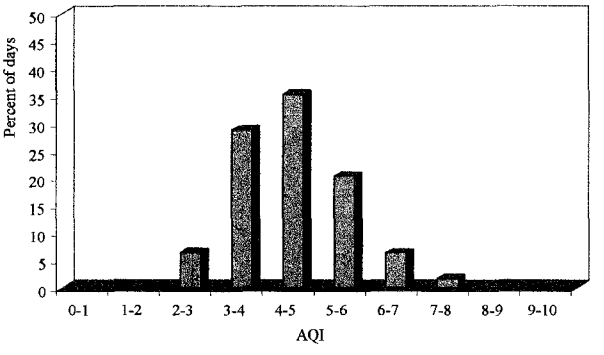


Figure 2c. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2

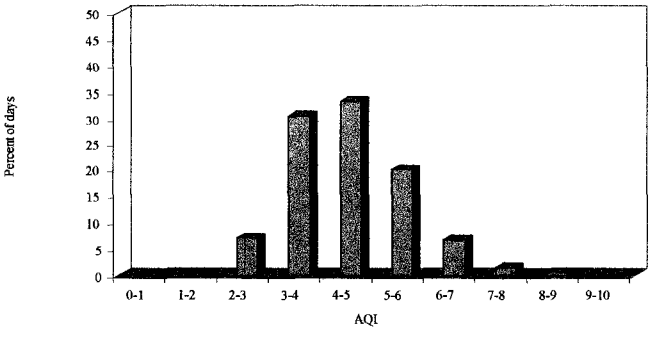


Figure 2d. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$

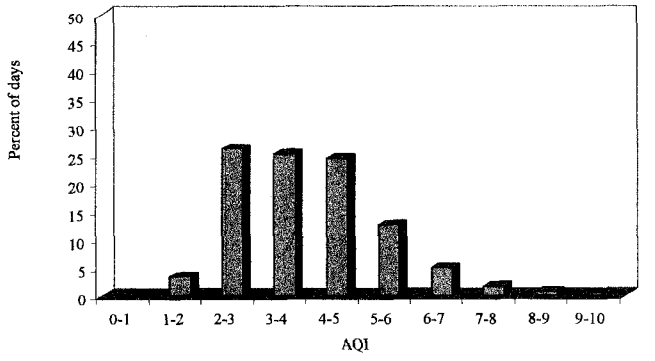


Figure 2e. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2, SO_2, CO

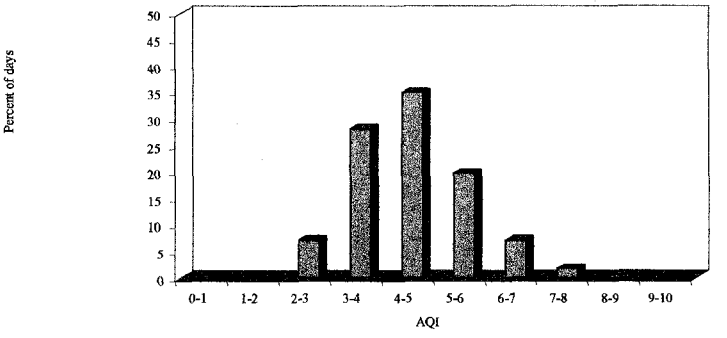


Figure 2f. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2, SO_2

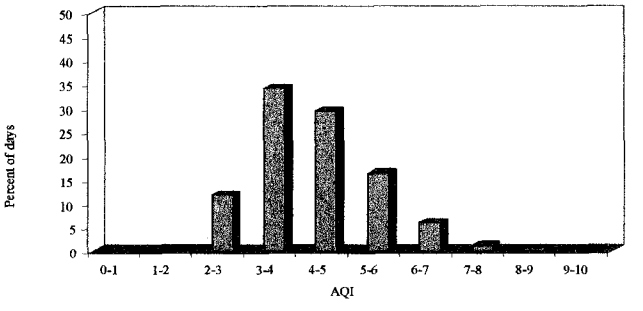


Figure 2g. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2

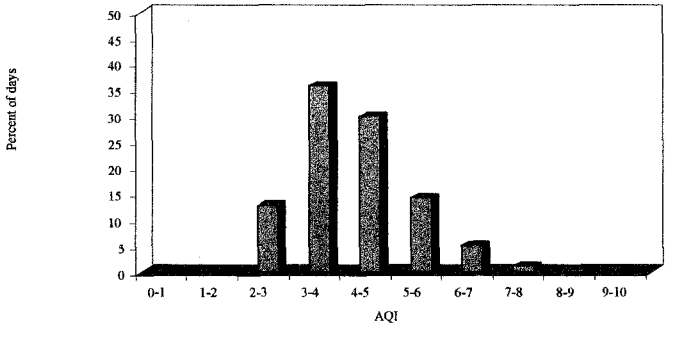


Figure 2h. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$

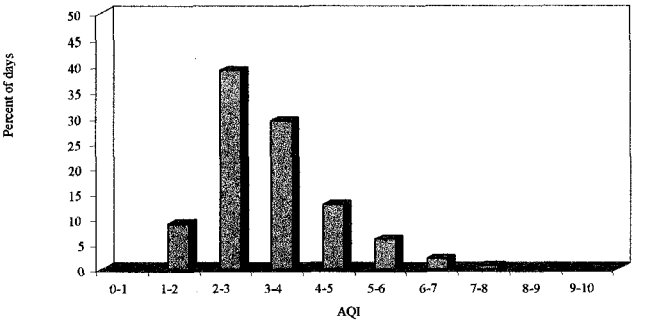


Figure 2i. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Meta-Analysis in relation to O_3, PM_{10}, NO_2, SO_2, CO

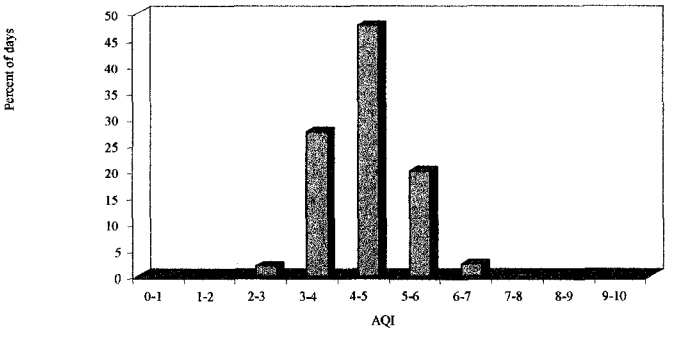


Figure 2j. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Meta-Analysis in relation to O_3, PM_{10}, NO_2, SO_2

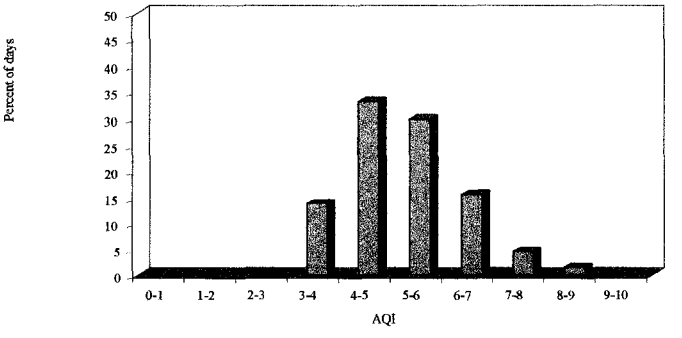


Figure 2k. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based on Meta-Analysis in relation to O_3, PM_{10}, NO_2

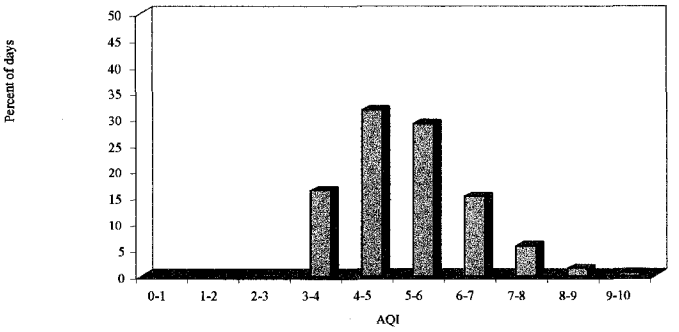


Figure 2l. Percent distribution of days, 1998-2000, across 10 cities, AQI formulation based Meta-Analysis in relation to O_3, PM_{10}

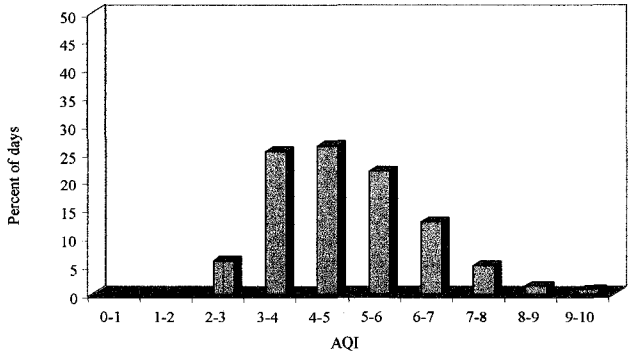


Table 5. Percent frequency of days at each AQI level for different AQI formulations, NAPS 1998-2000, 10 cities

AQI Level	Burnett study	Stieb study	Meta-Analysis
5-pollutant model			
0 to ≤3	4	7	2
>3 to ≤6	85	83	95
>6 to ≤10)	10	10	3
4-pollutant model			
0 to ≤3	7	12	0.4
>3 to ≤6	85	80	77
>6 to ≤10)	9	8	22
3-pollutant model			
0 to ≤3	7	13	0.5
>3 to ≤6	84	80	77
>6 to ≤10)	9	7	23
2-pollutant model			
0 to ≤3	30	48	6
>3 to ≤6	62	48	74
>6 to ≤10)	8	3	20

Spearman correlations were also calculated between the differing source regression coefficient HRBI formulations for the 5-pollutant and 4-pollutant models to assess the strength of association between the various formulations. The Spearman correlation coefficient is more robust than the Pearson correlation coefficient against outlying values and can be used to measure the consistency of the relationship between different formulations. In this case, we are interested in determining if the different formulations are consistent in their air quality ranking of days. There is a strong positive correlation between the various formulations showing consistency among the different formulations (Table 6).

Table 6. Spearman Correlations among index formulations, NAPS 1998-2000

	Burnett 5p[1]	**Stieb 5p**[2]	**MA 5p**[3]	**Burnett 4p**[4]	**Stieb 4p**[5]	**MA 4p**[6]
Burnett 5p	1.0	.	.	.	.	.
Stieb 5p	0.87	1.0	.	.	.	.
MA 5p	0.85	0.91	1.0	.	.	.
Burnett 4p	0.997	0.84	0.81	1.0	.	.
Stieb 4p	0.88	0.996	0.88	0.86	1.0	.
MA 4p	0.99	0.88	0.83	0.99	0.90	1.0

[1] AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2, SO_2, CO
[2] AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2, SO_2, CO
[3] AQI formulation based on Meta-analysis in relation to O_3, PM_{10}, NO_2, SO_2, CO
[4] AQI formulation based on Burnett study in relation to O_3, $PM_{2.5}$, NO_2, SO_2
[5] AQI formulation based on Stieb study in relation to O_3, $PM_{2.5}$, NO_2, SO_2
[6] AQI formulation based on Meta-analysis in relation to O_3, PM_{10}, NO_2, SO_2
*All correlations significant at <.0001

5.4.4 Hybrid Formulation

The AQI formulations based on the Burnett and Stieb health risk coefficients and the Meta-Analysis result in similar AQI level distributions. This supports the notion that the Burnett and Stieb health risk coefficients are in line with international findings summarized in the Meta-Analysis. The correlation analysis also shows a strong

association between the different HRBI formulations lending strength to the similarity of the different formulations. Given that both the Burnett and Stieb based formulations provide relevant information on the health risks due to air pollution in Canada, risk estimates from both of these studies were incorporated into the construction of a new health risk based AQI for Canada.

Risk estimates were combined to produce a new *hybrid* AQI formulation based on the general HRBI formulation described above. The two sets of risk estimates were combined by calculating the arithmetic mean of each pollutant's risk coefficients from both studies. These new mean risk coefficients were applied to the general HRBI formulation in equation 1. The hybrid risk estimates are reported in relation to the mean concentrations reported in the Stieb study and are presented in Table 7.

Table 7. Percent change in mortality at mean concentration for HRBI models

Pollutant	Mean conc'n [a]	Burnett study	Stieb study	Hybrid
NO_2	18.8	1.88	1.6	1.74
O_3	28.2	2.97	1.03	1.99
SO_2	4.6	0.34	0.72	0.53
$PM_{2.5}$	8.2	0.49	0.94	0.72
CO	0.7	0.47	0.56	0.51

[a] units are ppb for NO_2, O_3 and SO_2, ppm for CO and ug/m^3 for PM

The hybrid risk estimates were applied to the HRBI formulations for the different pollutant number models. The long-term distribution of HRBI values was also examined for this new hybrid formulation using the NAPS 10 city 1998-2000 dataset. The percent distribution of days at specific AQI levels for the different pollutant models is presented in Table 8. The results are similar to those observed for the AQI formulations relying on the Burnett and Stieb health risk coefficients. This is expected since the HRBI hybrid model represents a combination of these risk coefficients.

Table 8. Percent frequency of days for different HRBI hybrid models at specific AQI levels, NAPS, 1998-2000 10 cities

	HRBI Model			
AQI level	5-pollutant	4-pollutant	3-pollutant	2-pollutant
0 to ≤3	4.7	7.5	7.9	35.5
>3 to ≤6	85.2	84.5	84.5	58.3
>6 to ≤10	10.0	8.0	7.6	6.2

Assessment of Responsiveness

The hybrid formulations were applied to two Canadian cities for a preliminary assessment of their ability to detect known variations in air quality conditions. Two cities, Calgary and Windsor, with known historical differences in air quality conditions were chosen for this investigation. Daily NAPS data from 2001 were used in the investigation. The percent frequency of days at 0 to ≤3, >3 to ≤6, and >6 to ≤10+ AQI levels are presented in Table 9. For the city of Calgary, the great majority of days are distributed between the >3 to ≤6 range with approximately $1/10^{th}$ of values across all pollutant number formulations in the higher range and even less in the low range. Using air pollution data from Windsor, the majority of days are also found in the >3 to ≤6 range; however, there is a much higher percentage of days at the higher AQI range of >6 to ≤10+. This observation of greater numbers of days with 'poorer' air quality reflected by the increased health risk of the HRBI, is in accord with historical air quality information on the relative frequency of poor air quality days between the two cities. In addition, it is interesting to note that there is a large shift in percentage distributions when moving to a 2-pollutant formulation for both cities. This highlights the significant influence of NO_2 on the HRBI final values.

Table 9. Percent frequency of days at AQI levels using the AQI hybrid formulations for Calgary and Windsor, NAPS 2001 data

City	Percent 0 to ≤3	>3 to ≤6	>6 to ≤10+
Calgary			
5-pollutant	1.4	86.5	12.1
4-pollutant	1.6	89.8	8.5
3-pollutant	2.2	86.5	11.3
2-pollutant	24.5	66.5	9.1
Windsor			
5-pollutant	5.6	69.2	24.9
4-pollutant	5.1	64.1	30.8
3-pollutant	7.5	68.9	23.7
2-pollutant	32.0	45.2	22.8

5.4.5 Interim Formulation

Health Canada in consultation with members of the AQI Editorial and Management Committees, decided to develop an interim HRBI formulation that incorporated the scientific development thus far, time-averaging concerns and current monitoring evidence with respect to some of the key pollutants.

From the distributional comparisons, only very small changes were noted with the elimination of SO_2 from the formulations. Despite this, SO_2 has known significant health effects and is a concern for some Canadian cities with localized point sources such as fossil fuel generating stations and metal industries. Although CO is generally cited as one of the key pollutants of concern when examining air quality, in the two primary Canadian studies considered here, the effects of CO tend to be weak. Given that CO is primarily a marker for vehicle emissions, as is NO_2, it was determined that this source could be adequately represented in the index by NO_2, for which stronger effects tended to be observed. Additionally, the WHO has stated that current evidence from epidemiological and animal studies shows that common environmental exposures to CO

in developed countries do not have discernable atherogenic effects on humans[11]. It was also reasoned that should CO be dropped from the index formulation, this would increase the coverage of the index to a larger number of sites where CO is not measured. For these reasons, CO was excluded from further consideration in the HRBI formulation. This decision was not intended to signify that CO is not important for other air quality monitoring purposes, although at this time it was eliminated from the interim HRBI formulations.

As previously discussed in the introduction section on air quality epidemiology, shorter pollutant time averages are preferred for the purposes of reporting and forecasting of air quality to the public. Many provincial jurisdictions try to provide air quality reports every few hours with an aim to see this reporting increased to every hour so that people can plan their daily schedules around the most up to date information. This supports the overall purpose of the AQI to provide the public with accurate information on air quality conditions.

At this stage of HRBI development, the risk estimates used in the formulation are a result of epidemiological studies of daily mortality and air pollution. Additional analysis is being conducted to generate results at a shorter time scale through the use of emergency room data, which could presumably be linked to shorter time scales based on arrival times. In recognizing the importance of shorter time averages and until additional analyses have been completed directly linking 3-hour average air pollution concentrations to emergency department visits an interim measure was developed. This interim measure attempts to scale results based on 24-hour pollutant measurements to 3-hour average measurements, so that the new HRBI could be computed using 3-hour average pollutant

concentrations. The scaling approach is the same one previously used by the monitoring and data analysis working group during an earlier round of AQI deliberations[125]. It involves running the AQI formulation through alternative versions of the moving 3-hour average concentration: an unadjusted value (i.e. multiplied by 1), multiplied by 0.75, and multiplied by the ratio between 24-hour average and daily maximum 3-hour average concentration[126]. The rationale for these adjustments was to ensure that the magnitude of the concentration used in the index calculation was as close as possible to the values employed in the original studies from which the risk coefficients were derived. The approach which minimized the difference between the distributions of days was selected as the best-performing scaling approach. Through preliminary analytical work conducted by Health Canada and Environment Canada for the 4-pollutant and 2-pollutant models, the following results were obtained. Multiplying by 0.75 for all pollutants less O_3, resulted in a distribution of days among AQI categories closest to that using the 24-hour formulation[127]. Thus the closest match described above was used to develop the interim HRBI formulations. The interim formulations also used the same maximum value for both the 2- and 4-pollutant formulations so that the maximum value of the 4-pollutant 24-hour formulation was applied across all formulations. The interim HRBI formulations are summarized in the table below.

Table 10. Interim HRBI Formulations

Formulation	Description
HRBI 4p 24hr	$= (10/10.4)*100*(e^{(0.0007*O_3^{(C)})}-1) + (e^{(0.0009*PM_{2.5}^{(C)})}-1) + (e^{(0.0009*NO_2^{(C)})}-1) + (^{c(0.0011*SO_2^{(C)})}-1)$
HRBI 2p 24hr	$= (10/10.4)*100*(e^{(0.0007*O_3^{(C)})}-1) + (e^{(0.0009*PM_{2.5}^{(C)})}-1)$
HRBI 4p 3hr	$= (10/10.4)*100*(e^{(0.0007*(O_3^{(C)*1)})}-1) + (e^{(0.0009*(PM_{2.5}^{(C)*0.75)})}-1) + (e^{(0.0009*(NO_2^{(C)*0.75)})}-1) + (e^{(0.0011*(SO_2^{(C)*0.75)})}-1)$
HRBI 2p 3hr	$= (10/10.4)*100*(e^{(0.0007*(O_3^{(C)*1)})}-1) + (e^{(0.0009*(PM_{2.5}^{(C)*0.75)})}-1)$

C = concentration of pollutant

Italicized number represents scaling factor for 3-hour formulations

Subsequent to this preliminary scaling analysis, additional analysis has been conducted by Health Canada which has resulted in the alteration of the 3-hour scaling factors described above. However, the scaling factors described here were used for the comparison of AQI formulations conducted in this thesis.

5.5 Future work

The scaling adjustments mentioned above have undergone revision by Health Canada along with additional analysis to evaluate the combination of different health outcomes for a more comprehensive determination of air pollution associated health risk. Additional work using hospital admission and emergency room visit data continues to be undertaken. To satisfy objective 3 of this thesis, the interim formulations described above were applied in the AQI analytical comparison.

6.0 ANALYTICAL COMPARISON OF VARIOUS APPROACHES TOWARDS AQI FORMULATION

6.1 Summary of Objectives

The objective of this thesis component is to conduct a quantitative analytical comparison of various approaches towards AQI formulation. The criteria that were identified for index assessment in section three of this thesis, serve as the conceptual framework for informing an analysis into the properties of different AQIs. This section details a preliminary exploration of the characteristics of the HRBI with comparisons to other AQIs. Recommendations for an improved Canadian AQI formulation approach are presented. The AQIs that were suggested for comparison in section four of this thesis were used for this analysis.

6.2 Introduction

Comparative analysis or sensitivity analysis is an important component to the construction or formulation of a model. This is especially true when model results are associated with significant and important actions. This type of analysis involves investigating whether other reasonable alternatives for model construction will significantly affect the conclusions[128]. Sensitivity analysis is considered by some to be a pre-requisite to model building. Although acknowledged as such, it is often not conducted[129].

Sensitivity analysis is defined as "a method to determine the robustness of an assessment by examining the extent to which results are affected by changes in methods, values of variables or assumptions" [26]. The prospect that future observations may call the model into question always exists. Thus, an investigation and comparison of model

alternatives is reflective and in harmony with modeling itself by acknowledging that there may be other alternative models to represent the system being modeled. This exercise also lends confidence to the final model choice by highlighting differing strengths and weaknesses. Furthermore, assessing a model's response to alternative variable selections or variable aggregation methods (i.e. formulations) will also provide an increased understanding of the model itself. This understanding has guided the basis for the analytical comparison of various approaches towards AQI formulation. The AQI formulations represent different 'models' for reporting on air quality and the assessment of quantitative similarities and differences between these formulations is representative of a sensitivity analysis of different AQI formulations.

6.3 Methods

6.3.1 Conceptual Framework for Analytical Comparison

The index assessment criteria that were identified in section three of this thesis served as the conceptual framework for the analytical comparison. The approach taken was to develop practical research questions that would provide information on some of the properties of the different AQIs that could be used as a preliminary assessment of their strengths and weaknesses. The methods used in this preliminary exploration of index properties are described below.

The most basic assessment of an AQI's accuracy is determining whether increasing concentrations of air pollutants result in increasingly *worse* classifications of air quality by the index, and low level pollutant concentrations result in *better* classifications of air quality. Representing air quality accurately also ensures that current

research evidence on air pollution health effects is incorporated into the AQI formulation. Health effects are complicated by the contribution of multi-pollutant interactions and are found to occur at low levels of pollutant concentration with no observable thresholds for effect. Inconsistent air quality categorizations among indices also provide evidence that indices differ in their ability to accurately quantify air quality conditions. By investigating the pollutant concentrations underlying these inconsistent categorizations, evidence can be gathered for which index might in fact be more accurate. The following research questions were developed to try to gather evidence for the first basic assessment of determining whether increasing pollutant concentrations result in worse air quality categorizations:

1. What are the results of each AQI formulation when inputting moderate-level pollutant concentrations, versus higher-level pollutant concentrations?
2. Are 'high/poor' air quality index values being calculated when there are high pollutant concentrations?
3. What are the pollutant concentrations underlying 'high/poor' air quality index values and *outlier* values?

Question 1 was evaluated by entering specific pollutant concentrations into each of the AQI formulations to calculate the respective AQI values and categorizations. The moderate and high pollutant concentrations were determined using data from NAPS for 10 Canadian cities for the years 1998-2000 and calculating the median, 75^{th} percentile and 95^{th} percentile pollutant concentrations for each pollutant. Higher pollutant concentrations should be associated with higher AQI values and worsening air quality categorizations. The results of this analysis were also used to assess each AQI's

responsiveness to multiple pollutants by examining the effect of equally high pollutant concentrations among all pollutants on air quality categorizations. In particular, the moderate pollutant concentrations were examined to identify whether moderate levels among all pollutants would result in 'high/poor' air quality categorizations.

To evaluate questions 2 and 3 the maximum AQI value and the second highest AQI value for each formulation were identified. The specific hours associated with these values were also determined so that the pollutant concentrations at these particular times could be examined. Additionally, hours with inconsistent air quality categorizations among the formulations were identified using plots of the hourly change in AQI values among the different AQI formulations so that the pollutant concentrations underlying these values could be examined. This involved identifying peak values in some AQI formulations that were not observed in the other formulations. This investigation was used to examine the basic criteria of higher pollutant concentrations resulting in 'higher/poorer' air quality categorizations, but also offered the opportunity to investigate whether each AQI formulation was driven by threshold pollutant concentrations. In particular the inconsistent AQI values allowed for a deeper investigation into understanding the pollutant concentration response associated with each formulation. Further, the multi-pollutant responsiveness was also assessed by examining the underlying pollutant concentrations and their effect on the resultant AQI values.

The relevance of the pollutant variables to the overall AQI values was also investigated. The pollutant variables for each AQI were chosen based on research evidence demonstrating their relevance to air quality. However, a quantitative assessment of this relevance would specifically highlight whether each pollutant made a

contribution to the overall AQI value for each formulation. The research questions that were developed to describe this index property were:

4. What is the percentage contribution of each pollutant to the HRBI index formulations?
5. What is the percentage of hours for which each pollutant was the driver?
6. What is the percentage of hours for which each pollutant was the driver during 'high/poor' air quality index values?

Question 4 was only applicable to the HRBI formulations since the HRBI formulations represent weighted sums of the different pollutants that contribute to an overall AQI value. The Root Sum Exponential Formulations were excluded from this investigation because of the difficulties previously discussed in making quantitative interpretations with these formulations. The individual pollutant weighted values for the HRBI formulations were transformed into percentages reflecting their percentage contributions to the overall AQI values. These percentage contributions were calculated using all of the available air pollution data to determine which pollutants made the most contribution to the final AQI values and the frequency at which each pollutant made significant percentage contributions to the final AQI values. A pollutant making high contributions for a large percentage of hours to the final AQI value would demonstrate relevance to the AQI. The methods for evaluating questions 5 and 6 involved determining which pollutant made the highest percentage contribution to the overall AQI values for the HRBI formulations, and determining which pollutant was the maximum operator pollutant for the U.S. PSI and Ontario AQI indices. The identified pollutant was defined as the pollutant driver. The number of times each pollutant was the driver was

calculated and expressed as a percentage of the total hours or total hours where the AQI was considered 'high/poor'. The results of this analysis provided information on the influence of each pollutant in driving the overall AQI values. Determining that a pollutant was the driver during 'high/poor' hours would demonstrate that the pollutant was important in categorizing air quality.

The AQIs used in the analytical comparison were also compared with each other and assessed for relationship consistency among their data values. The following research question was used for this assessment:

7. What is the correlation between different AQI formulations?

Question 7 was evaluated by calculating Spearman correlations among the different AQI formulations. The formulations with the strongest positive correlations were further compared to identify any similarities that would explain their stronger positive correlation. The results of question 3 were also examined to determine whether the hours associated with the maximum AQI values were consistent across formulations.

The criteria for index assessment also describe the need for an index to be responsive to variable changes and sensitive enough to be able to detect changes. Translating this to the AQI context and the available data for analysis, the following research questions were asked to provide further information on the functionality of the indices:

8. How do AQI values differ between different cities?
9. How do AQI values differ between seasons?
10. Is the AQI able to capture shorter-term pollutant peak events?

The average and maximum AQI values and the percentage of AQI values categorized as 'high/poor' associated with each formulation for each city were compared. This investigation was carried out to determine if the variations among AQI values for each city were in accord with historical and generally accepted city variations.

Seasonal variations of air quality are also known to exist among these Canadian cities with generally higher levels of pollutant concentrations in the summer months. Thus, for question 9, the AQIs were reviewed for seasonal variations. The plots of hourly changes associated with each of the AQI formulations were used for this examination.

Question 10 was evaluated using the results of the outlier investigation in question 3. For this investigation into pollutant peak events, time points were identified that had higher pollutant concentrations lasting for only a short duration. The AQI values for each formulation were examined to determine if these short term events resulted in higher AQI categorizations.

The AQIs were also compared to determine whether there were any theoretical or empirical advantages of one AQI formulation over another. An overall assessment of the findings related to the above questions was conducted so that potential strengths for one formulation over another could be identified. In addition, the AQIs were each examined against the AQI shortcomings previously described in the introduction. This provided additional scientific and policy-related rationale for assigning strengths to one AQI formulation over another.

The final comparison of AQIs related to user-considerations. The user-considerations that were assessed included: transparency, complexity and feasibility. Transparency was examined by determining whether documentation was available for

each AQI formulation detailing the rationale and developmental work underlying the formulation. To assess complexity the AQI formulations and associated documentation were reviewed for analytical uncertainties, outstanding questions or documented recommendations for further developmental work. For feasibility assessment the AQIs were reviewed for their data requirements (i.e. required pollutants and time-averages). In addition, the potential resource requirements, for example development of a new messaging model and public education, were also described for each AQI formulation.

6.3.2 AQI Formulations used in Comparison

The review of AQI formulations generated a list of different formulations for comparison. The following AQI formulations were examined in this AQI analytical comparison:

1. **US EPA AQI** (AQIEPA)

$$\text{Sub-index } (i) = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} (C_p - BP_{Lo}) + I_{Lo}$$

where, C_p is the concentration of pollutant (i), BP_{Hi} is the breakpoint conc'n that is greater than or equal to C_p, BP_{Lo} is the breakpoint conc'n that is less than or equal to C_p, I_{Hi} is the AQI value corresponding to BP_{Hi}, and I_{Lo} is the AQI value corresponding to BP_{Lo}. The final AQI is the value of the maximum sub-index[130].

2. **Ontario MOE AQI** (AQIONT)

$$\text{Sub-index } (i) = A + B^* [i]$$

where, A is the y-intercept of segmented linear function for i^{th} pollutant and concentration level, B is the slope of segmented linear function for i^{th} pollutant and concentration level

and [i] is the concentration of the i^{th} pollutant. The final AQI is the value of the maximum sub-index [131, 132].

3. **Health Risk Based AQI**
   a. 4 pollutant 24-hour formulation (HRBI 4p 24hr)
   b. 2 pollutant 24-hour formulation (HRBI 2p 24hr)
   c. 4 pollutant 3-hour formulation (HRBI 4p 3hr)
   d. 2 pollutant 3-hour formulation (HRBI 2p 3hr)

$$\mathrm{AQI} = (10/c)\sum_{i=1\ldots m} 100\left(e^{\beta_i x_i} - 1\right)$$

as previously described in equation 3. All formulations have the same scaling factor 'c'. The formulations based on different time averages have different adjustment factors for each pollutant, see Table 10.

4. **Root Sum Exponential** (Swamee and Tyagi[85])
   a. with Ontario Ambient Air Quality Criteria (S&T_ONT)
   b. with HRBI 4 pollutant 24 hour average risk estimates (S&T_Hyb)

$$I = \left(\sum_{i=1}^{n} si^{2.5}\right)^{0.4}$$

where I is the AQI and si is the sub-index for each pollutant, and is determined by:

$$si = s_s\,(q/q_s)^m$$

where s_s is the scaling coefficient, q is the pollutant concentration, q_s is the standard pollutant concentration and m represents the sub-index constant. The table below summarizes the Ontario Ambient Air Quality Criteria used as *standards* to determine the sub-indices (si) in the S&T_ONT formulation. A scaling coefficient of 100 was used so that the results would be comparable to the 100 scale used for the AQIONT.

Table 11. Ontario ambient air quality criteria (Ontario Ministry of Environment, 2004)

	O_3 (ppb)	$PM_{2.5}$[a] (ug/m^3)	NO_2 (ppb)	SO_2 (ppb)	CO (ppm)
S&T_ONT	80	30	200	250	30

[a] There is no Ontario air quality criterion for $PM_{2.5}$, thus the Canada Wide Standard of $30ug/m^3$ was used.

For the S&T_Hyb formulation, the health risk estimates from the HRBI 4 pollutant 24-hour formulation were used as *standards*. A common risk estimate was chosen among all pollutants that reflected the range of risk estimates observed. A risk estimate of 0.01 was chosen to reflect a one percent increase in risk. The regression coefficients (β) associated with each risk estimate were computed so that the common risk estimate of 0.01 could be applied and the pollutant concentration associated with this risk could be determined. Thus, an associated standard for each pollutant was calculated using the formula below and solving for the pollutant concentration (Ci) when pi = 1 (representing 0.01 relative risk). This concentration is reflective of the associated pollutant *standard* for a one percent increase in health risk. The scaling coefficient was assigned as 1 for this formulation to allow for the comparison of results with the other HRBI formulations. This is represented by the following formula:

$$\beta = (\ln(1 + pi/100))/Ci$$

where, pi is the percent change in risk for ith pollutant and Ci is the mean concentration for ith pollutant.

Table 12. Calculated *standards* using regression coefficients from HRBI 4-pollutant and 24-hour averaging model for a one percent increase in risk

	O_3 (ppb)	$PM_{2.5}$ (ug/m^3)	NO_2 (ppb)	SO_2 (ppb)
S&T_Hyb	14.2	11.4	10.8	8.7

In each of the formulations above, the pollutant concentrations that are inputted into the formulation represent different moving averages for the concentration of that

pollutant at each specific hour of calculation. A moving average is the average pollutant concentration for a specified number of time periods. At each subsequent hour, the average "moves" because the latest number of time periods is used. Table 13 presents the associated time averaging applied to each pollutant for each formulation for the calculation of the moving average.

Table 13. Time Averaging Details of Index Formulations

	O_3	$PM_{2.5}$	NO_2	SO_2	CO
AQIEPA[a]	1hr and 8hr	24 hr	24 hr	24 hr	8hr
AQIONT	1hr	3hr	1hr	1hr	1hr
HRBI 4p 24hr	8hr	24hr	24hr	24hr	-
HRBI 2p 24hr	8hr	24hr	-	-	-
HRBI 4p 3hr	3hr	3hr	3hr	3hr	-
HRBI 2p 3hr	3hr	3hr	-	-	-
S&T_Hyb	8hr	24hr	24hr	24hr	-
S&T_ONT	1hr	24hr	1hr	1hr	1hr

[a] There is no short term NAAQS for NO_2.

6.3.3 Description of the Data

The move towards real-time reporting and the evidence of the short-term effects of acute concentrations of pollutants necessitated a dataset that contained short-term concentrations of pollutants. Hourly air pollution data were obtained from the Ontario Ministry of the Environment (OMOE) for the period of 1990 to 2001 for selected Ontario Monitoring sites. The sites included: Hamilton, Toronto, Ottawa and Windsor. The data were provided in excel format, organized by pollutant, day and hour. The concentrations of the pollutants were reported in ppm for CO, ppb for O_3, NO_2 and SO_2, and ug/m^3 for $PM_{2.5}$. Table 14 presents a sample of the hourly AQI data provided by the OMOE. With hourly data, it is possible to calculate hourly moving averages for pollutant concentrations to accommodate the averaging time requirements of each AQI.

Table 14. Sample of Hourly Air Quality Data File Provided by OMOE

Pollutant Code[1]	Station[2]	Date	HR01	HR02	HR03	HR04	HR05	HR06	HR07	HR08	HR...	HR24
124	12008	1-Jan-01	0	0	1	0	0	0	1	0	...	2
124	12008	2-Jan-01	4	4	4	4	4	3	5	7	...	10
124	12008	3-Jan-01	10	9	7	8	6	5	4	8	...	11
124	12008	4-Jan-01	7	7	7	4	4	2	4	2	...	5

[1] Pollutant Code 124 = Fine Particulate Matter (ug/m^3)
[2] Windsor Downtown – 467 University Avenue West

6.3.3.1 Data Considerations

The comprehensiveness of the pollutant information varied for each site. For comparative purposes it was important that the data set used in the analysis contain information on the five key pollutants so that all formulations could be properly calculated and compared. In the interest of using the greatest amount of available comparable information, different dataset timeframes were selected for each site depending on the availability and monitoring of the five key pollutants. The table below shows the time frames selected for each site and provides some explanation for the rationale of each selection. Although city comparisons would also be conducted in the analysis, the importance of the comparisons focused on the AQI formulations themselves.

Table 15. Description of Monitoring sites and Data Time Frames Selected, OMOE

City	Station #	Time Frame selected	Comments
Hamilton	29000	1998-2001	• $PM_{2.5}$ data available from Jan.1, 1998 • ***Decided to use data from 1998-2001 to have full suite of pollutants for AQI calculations*** • May 17-18, 1998 & July 22, 1998 & March 26, 1999 – March 31, 1999 were also not available and were not included
Toronto	31103	1998 and 2001	• $PM_{2.5}$ data available from Aug.15, 1997 • Since 1962, the station location has changed 7 times which has resulted in missing and invalid data during these periods of transition • There is a large percentage of invalid data for

City	Station #	Time Frame selected	Comments
			SO_2, CO and $PM_{2.5}$ between April 20, 1999 and April 5, 2000 • ***Decided to use data from 1998 and 2001 to have full suite of pollutants for AQI calculations over an entire year*** • March 27, 1998 – March 31, 1998 were also not available and were not included
Ottawa	51001	1998-2001	• $PM_{2.5}$ data available from Nov.21, 1997 • ***Decided to use data from 1998-2001 to have full suite of pollutants for AQI calculations*** • January 9, 1998 – January 18, 1998 were also not available and were not included
Windsor	12008	2001	• $PM_{2.5}$ data available from Jan.1, 2001 • ***Decided to use data from 2001 to have full suite of pollutants for AQI calculations***

Data that were unavailable were considered different from missing or invalid data because they represented information that was unavailable for all pollutants and were separately indicated by the data provider, the Ontario Ministry of Environment. These unavailable days were excluded from the total number of days examined for each site.

Even though a few years or in some cases only one year's worth of data are used in analysis, the data represent hourly pollutant concentrations, representing very large working datasets. These large datasets are at a minimum a year in length and thus represent an annual picture of air quality conditions to provide an understanding on how the different formulations function over the course of a year. Since the data were provided by the OMOE, the working dataset had previously undergone formatting and data quality assessments. Thus invalid or missing data were already identified. Although data quality documentation is unavailable, the data source itself represents a credible source of information for air quality data.

When working with the data for comparative analysis, transformation of the data was undertaken so that time averages for the pollutants could be calculated. This involved transposing of the data to accommodate the calculation of moving hourly averages of each pollutant as specified by the requirements of each formulation.

6.3.3.1.1 Handling of Missing Data

In the database: Missing data were indicated in the database by blanks and invalid data were indicated by -999. As already stated, unavailable data were differentiated from missing or invalid data. No imputations were performed for any hours with unavailable, missing or invalid data.

In the analysis: The timeframes selected represent a minimum of one year's worth of data for Windsor and up to 3 years for Hamilton and Ottawa. Thus, each site specific dataset consisted of a large dataset for analysis as hourly information for pollutants was provided. Those pollutant hours with missing data as well as invalid data (-999) were included in the majority of analyses. They were included in the sum of total values but were excluded from the specific AQI formulation calculations. The decision to include these data reflected a need to represent real-world conditions for AQI calculation. Thus, a missing or invalid concentration for one pollutant did not result in the exclusion of that entire day or hour's worth of pollutant information from analysis. In real-world conditions AQIs are calculated with the information available, and thus this same process was applied in the analysis. An analysis was done to assess the number of days when the AQI formulations were calculated with missing pollutants to assure that

the results reflected hours where the majority of the time full pollutant information was available.

As previously described, all of the formulations involve an averaging time for pollutant concentrations. In the calculation of moving averages for the different formulations, the guideline applied for the NAPS data is used. A minimum requirement of 75 percent of the hours was required for the determination of a moving average[126]. Thus for a 24-hour moving average, the current hour and the preceding 23 hours worth of data were averaged for a 24-hour moving average. At least 18 hours worth of data were required to calculate this moving average. Thus, if only 18 hours worth of data were available, a 24-hour moving average would be calculated by averaging the available 18 hours worth of data. If this 75 percent guideline was not met the moving average pollutant concentration for that hour was assigned as missing. For the calculation of 3-hour averages, the 75 percent guideline was increased to 100 percent so that the current hour plus the 2 preceding hours were required for the calculation of the 3 hour moving average.

In the case where moving average pollutant concentrations were missing for the HRBI formulations, these moving average pollutant concentrations were set to zero. The reason for this was to enable the calculation of the final index value for the HRBI formulations even when one or more moving average pollutant concentrations were missing. There are some instances where analytical comparisons were conducted to assess the contribution of each pollutant as the driver, only those hours where all pollutants were available were examined. This was done to avoid any bias incurred

because of missing pollutants. Further clarification of the handling of missing data will be noted in each pertinent section.

6.3.4 Description of Analysis

Analyses were conducted using SAS version 8.2 (SAS Institute Inc., Cary, NC, USA) and Microsoft Excel 2002 (Microsoft Office XP, Microsoft Corporation). In addition to the analyses indicated in the Conceptual Framework for Analytical Comparison, some additional descriptive analyses were undertaken to better understand the different formulations and inform some of the analyses for the analytical comparison. These included: 1) identifying the extent of missing and invalid pollutant concentrations on AQI calculations; 2) summary statistics for each of the pollutants to identify mean and maximum pollutant concentrations as well as an investigation into the distribution of pollutant concentrations in each of the city specific datasets; 3) summary statistics for each of the AQI formulations to identify the mean and maximum AQI values associated with each formulation as well as an assessment of the variability in AQI values; 4) determining how often AQI values were calculated based on differing numbers of pollutants as a result of missing or invalid pollutant concentrations; 5) plots of the hourly changes associated with each of the AQI formulations to help identify peak values and inconsistent air quality categorizations among the different AQI formulations; 6) bar charts of the percent distribution of AQI values associated with specific AQI category assignments for each formulation and 7) determining the percentage of AQI values categorized as 'high/poor' for the different AQI formulations.

To examine the percent distribution of AQI values for each formulation, the AQI values were grouped to different categories for each AQI formulation. For the AQIONT and AQIEPA formulations, the categories currently used in practice were used for their categorical distribution. For the HRBI formulations, each integer value from 0 to10 was used to classify the AQI values. With no existing categorizations for the S&T formulations, those used for the HRBI and AQIONT formulations were also applied to the S&T_Hyb and S&T_ONT formulations respectively. These categorizations were chosen because the *standards* used in the S&T formulations were adopted from these other formulations; however, they may not be applicable to these new formulations and are only included here for a qualitative assessment.

To determine the percentage of AQI values categorized as 'high/poor' among the different AQI formulations, the 'high/poor' categorizations that were used need to be specified. The 'poor' categories used in current practice for the AQIONT and AQIEPA were also used for this analysis. For the HRBI formulations the 85^{th} percentile of each interim HRBI formulation using the original NAPS 1998-2000 data set was used as the criterion for the determination of 'high' air pollution values. This percentile was previously used in the study by Stieb et al. and is representative of values at the extreme end of the distribution which would likely signify a notably increased level of health risk associated with air pollution conditions. For the S&T formulations, the 85^{th} percentile index value determined for the HRBI 4p 24hr was used as the index value for the designation of 'high' for the S&T_Hyb formulation. Similarly, the 'poor' index value of >49 was used for the 'poor' categorization of the S&T_ONT index values.

6.4 Results

6.4.1 Description of the Data and AQI Formulations

Extent of missing and invalid pollutant concentrations

The number of hours with valid air pollution data that could be used in AQI determinations for the timeframes selected and for each study site are presented in Table 16. In a full year, there are 8,760 hours of pollutant data, except for leap years such as 2000 where there are 8784 hours. The timeframes selected were chosen so that there would be good coverage of the 5 key pollutants. The number of hours with valid pollutant data is generally consistent across all pollutants and valid pollutant concentrations are available for the great majority of hours. Missing data for all pollutants never exceeded three percent of all total hours, and invalid data never exceeded seven percent of the total hours. The highest missing and invalid percentages are observed for $PM_{2.5}$ concentrations, reflecting the relatively new adoption of continuous monitoring for $PM_{2.5}$. Overall the site specific datasets represent very good coverage.

Table 16. Number of Hours (percent of total hours) with Valid Pollutant Concentration Data at Select Ontario Air Monitoring Sites

	SO_2	NO_2	CO	O_3	$PM_{2.5}$
Hamilton n=34,848 (1998-2001)					
Total Valid	34,532 (99.09)	34,450 (98.86)	34,074 (97.78)	34,513 (99.04)	33,495 (96.12)
Missing	126 (0.36)	115 (0.33)	293 (0.84)	141 (0.40)	857 (2.46)
Invalid	190 (0.55)	283 (0.81)	481 (1.38)	194 (0.56)	496 (1.42)
Toronto n=17,400 (1998 and 2001)					
Total Valid	17,014 (97.78)	17,178 (98.72)	17,151 (98.57)	17,041 (97.94)	17,064 (98.07)
Missing	38 (0.22)	1 (0.01)	60 (0.34)	36 (0.21)	18 (0.10)
Invalid	348 (2.00)	221 (1.27)	189 (1.09)	323 (1.86)	318 (1.83)
Ottawa n=34,824 (1998-2001)					
Total Valid	33,951 (97.49)	33,623 (96.55)	34,226 (98.28)	33,513 (96.24)	32,581 (93.56)
Missing	184 (0.53)	89 (0.26)	202 (0.58)	179 (0.51)	89 (0.26)
Invalid	689 (1.98)	1112 (3.19)	396 (1.14)	1132 (3.25)	2154 (6.19)
Windsor n=8,760 (2001)					
Total Valid	8,680 (99.09)	8,589 (98.05)	8,487 (96.88)	8,688 (99.18)	8,308 (94.84)
Missing	1 (0.01)	1 (0.01)	1 (0.01)	1 (0.01)	1 (0.01)
Invalid	79 (0.90)	170 (1.94)	272 (3.11)	71 (0.81)	451 (5.15)

Descriptive statistics of the air pollutants

Some basic descriptive statistics for each pollutant for each specific site are presented in Table 17. The mean and maximum concentrations for SO_2 are lowest in Ottawa and Toronto. Considering that this pollutant is generally found in ambient air due to industrial pollution, this finding is consistent with the industrial nature of the Ontario sites. However, the median concentration is the same for Hamilton, Toronto and Ottawa and is approximately the same for Windsor. Upon examination of the skewness, it is found that the distribution of values tends to have a slightly positive skew, which tend to increase the mean value as compared to the median. The positive skew and relatively large standard deviations as compared to the mean values suggest that there is a greater variability in SO_2 concentrations as compared to the other pollutants. NO_2 is lowest in Ottawa, which is reflective of the lower level of industrial and vehicular pollution in that

area. Toronto has the highest mean and median NO_2 concentrations which are representative of the high levels of traffic in the area contributing to increased NO_2 concentrations. The CO mean and even maximums represent low concentrations across the different sites. The highest mean and median concentrations are found in Toronto, as expected since the majority of CO pollution comes from the transportation sector. For the Hamilton dataset, the mean and median CO concentrations happen to be the same even though the data are skewed to the right. This is probably due to a large proportion of values around the lower bounds of the data (0.00 ppm). The O_3 mean and median concentrations were relatively consistent across all sites. However, Toronto has a notably higher maximum because there is an abundance of NO_x from the transportation sector and VOC's, which in the presence of sunlight react to form ground-level ozone. Additionally, there is a significant amount of cross-border pollution where O_3 and O_3 forming compounds are carried into Ontario from the U.S. This is particularly relevant for Windsor, which rests on the Canada-U.S border. $PM_{2.5}$ mean and maximum concentrations are highest in Hamilton, which is reflective of the industrial pollution contributing to increased $PM_{2.5}$. For all pollutants, generally large standard deviations are found, reflecting a great deal of variability among the pollutant concentrations. This is expected considering the seasonal nature and localized sources for some of the pollutants.

Table 17. Descriptive Statistics of Pollutants excluding Invalid Values for Selected Ontario Monitoring Sites

	Mean	Median	Std. Dev.	Minimum	Maximum	Skewness
SO_2						
Hamilton	6.01	3.00	7.93	0	107	3.28
Toronto	4.50	3.00	3.57	0	65	2.93
Ottawa	3.51	3.00	3.26	0	67	1.71
Windsor	6.09	4.00	7.25	0	82	2.86

	Mean	Median	Std. Dev.	Minimum	Maximum	Skewness
NO_2						
Hamilton	22.08	20.00	11.24	0	96	0.89
Toronto	27.37	26.00	11.68	0	92	0.80
Ottawa	13.17	11.00	10.31	0	93	1.25
Windsor	19.36	17.00	10.09	1	87	1.13
CO						
Hamilton	0.85	0.85	0.39	0	7.28	2.18
Toronto	1.02	1.00	0.42	0	4	0.82
Ottawa	0.80	0.70	0.52	0	4	1.52
Windsor	0.26	0.18	0.31	0	4.94	3.73
O_3						
Hamilton	18.59	16.00	16.07	0	98	1.12
Toronto	19.94	17.00	16.04	0	136	1.20
Ottawa	21.25	20.00	13.90	0	95	0.79
Windsor	20.50	17.00	17.98	0	112	1.19
$PM_{2.5}$						
Hamilton	11.70	9.00	10.04	0	108	1.75
Toronto	9.66	7.00	8.81	0	78	2.00
Ottawa	7.05	5.00	6.81	0	55	1.92
Windsor	9.41	7.00	8.62	0	72	1.73

Descriptive statistics of the AQI formulations

Tables 18 to 21 summarize some of the descriptive properties of the formulations used in the AQI analytical comparison. The HRBI 3-hour formulations across all sites have slightly smaller numbers of total valid AQI values because they require that pollutant concentrations are available for all three hours to calculate a 3-hour moving average. Thus, even though the AQIONT has a shorter averaging time of one hour for most pollutants, there are more valid AQI values since there is no requirement to have the two preceding hourly concentrations. With the 24-hour and 8-hour averaging times the minimum requirement is that at least 75 percent of the 24 or 8 hours are present, allowing for greater flexibility when dealing with missing or invalid pollutant concentrations. Overall the missing and invalid values make up a very small percentage of the total values across all cities, representing good coverage for the calculation of AQI values

using different formulations. Among the HRBI formulations, the highest means are found with the HRBI 4p formulations showing the additive contribution of the different pollutants. The HRBI 2p formulations generally have a larger positive skew across their distribution of values showing a greater concentration of lower AQI values.

Upon comparison of each Ontario site, the city of Ottawa has the lowest mean, median and maximum values across all formulations. Hamilton has the highest mean AQI value when using the AQIEPA and AQIONT formulations. Conversely, Toronto has the highest mean and median AQI values using the HRBI 4p formulations, although Hamilton has the highest maximum values. The mean and median values with the HRBI 2p 24hr formulation are also greatest for Hamilton. When applying the HRBI 2p 3hr formulation all cities rank very closely, with Hamilton having slightly higher mean and median values but Windsor ranking the highest among the maximum values. The S&T_Hyb formulation has the largest mean value for Toronto, which corresponds with the results of the HRBI 4p 2hr formulation. The S&T_ONT has the highest mean, median and maximum values for Hamilton similar to what was found when using the AQIONT.

Table 18. Descriptive Statistics of Index Formulations, Hamilton, 1998-2001

	N	Missing & Invalid	Mean	Median	Std. Dev.	Min. Value	Max. Value	Skewness
AQIEPA	34,766	82 (0.24)	36.16	31.11	20.60	2.21	153.03	1.05
AQIONT	34,676	172 (0.49)	18.92	16.65	10.74	0.09	99.73	1.10
HRBI 4p 24hr	34,766	82 (0.24)	4.82	4.43	1.90	0.51	15.01	1.13
HRBI 2p 24hr	34,760	88 (0.25)	2.20	1.86	1.38	0	10.21	1.49
HRBI 4p 3hr	34,568	280 (0.80)	3.92	3.49	1.75	0.02	17.97	1.57
HRBI 2p 3hr	34,563	285 (0.82)	1.97	1.61	1.35	0	9.80	1.58
S&T_Hyb	34,766	82 (0.24)	2.59	2.43	0.89	0.51	7.28	1.00
S&T_ONT	34,789	59 (0.17)	47.23	40.32	26.84	3.33	231.13	1.52

Table 19. Descriptive Statistics of Index Formulations, Toronto, 1998 and 2001

	N	Missing & Invalid	Mean	Median	Std. Dev.	Min. Value	Max. Value	Skewness
AQIEPA	17,301	99 (0.57)	31.46	25.84	18.56	0	141.62	1.57
AQIONT	17.275	125 (0.72)	17.60	15.00	9.99	0.61	89.55	1.25
HRBI 4p 24hr	17,299	101 (0.58)	5.05	4.71	1.70	0.42	14.24	1.31
HRBI 2p 24hr	17,284	116 (0.67)	2.13	1.76	1.36	0.08	10.34	1.72
HRBI 4p 3hr	17,231	169 (0.97)	4.10	3.77	1.53	0	12.11	1.36
HRBI 2p 3hr	17,226	174 (1.00)	1.93	1.56	1.34	0	11.13	1.79
S&T_Hyb	17,299	101 (0.58)	2.87	2.75	0.82	0.41	7.23	1.05
S&T_ONT	17,331	69 (0.40)	43.59	36.44	24.60	2.40	199.96	1.91

Table 20. Descriptive Statistics of Index Formulations, Ottawa, 1998-2001

	N	Missing & Invalid	Mean	Median	Std. Dev.	Min. Value	Max. Value	Skewness
AQIEPA	34,758	66 (0.19)	25.87	22.73	14.27	1.06	110.79	1.62
AQIONT	34,597	227 (0.65)	16.39	15.00	8.29	0	60.03	0.90
HRBI 4p 24hr	34,766	58 (0.17)	3.49	3.32	1.43	0.18	11.33	0.94
HRBI 2p 24hr	34,673	151 (0.43)	1.96	1.78	1.07	0.02	9.16	1.43
HRBI 4p 3hr	34,450	374 (1.07)	2.92	2.79	1.29	0	10.84	0.92
HRBI 2p 3hr	34,386	438 (1.26)	1.80	1.61	1.07	0	9.48	1.48
S&T_Hyb	34,766	58 (0.17)	1.98	1.91	0.76	0.18	6.13	0.93
S&T_ONT	34,743	81 (0.23)	36.74	33.24	19.00	0.97	160.82	1.58

Table 21. Descriptive Statistics of Index Formulations, Windsor, 2001

	N	Missing & Invalid	Mean	Median	Std. Dev.	Min. Value	Max. Value	Skewness
AQIEPA	8,737	23 (0.26)	31.34	26.42	18.46	2.76	121.95	1.31
AQIONT	8,704	56 (0.64)	18.13	16.37	10.39	0	73.27	1.09
HRBI 4p 24hr	8,737	23 (0.26)	4.50	4.28	1.67	0.90	12.82	1.04
HRBI 2p 24hr	8,735	25 (0.29)	2.13	1.75	1.42	0.15	9.19	1.62
HRBI 4p 3hr	8,657	103 (1.18)	3.73	3.46	1.56	0	12.26	1.19
HRBI 2p 3hr	8,656	104 (1.19)	1.95	1.57	1.43	0	11.27	1.75
S&T_Hyb	8,737	23 (0.26)	2.44	2.31	0.85	0.51	6.71	1.21
S&T_ONT	8,745	15 (0.17)	42.86	36.49	24.85	5.45	178.85	1.56

Frequencies of AQI values based on differing numbers of pollutants

Under real world conditions there are both hours and days where not all pollutant concentrations are available, but nonetheless AQIs are still reported using the available air pollution information. An investigation was conducted to assess the frequency with

which AQIs were calculated based on differing numbers of pollutants to ensure that the results of the AQI values were representative of the stated formulations. Tables 22 to 25 show that across all cities and all formulations over 85 percent of the index values had 0 pollutants missing for the calculation of each formulation. Less than 10 percent of index values had one pollutant missing and a very small percentage of index values had 2 or more pollutants missing when AQI values were calculated. Thus, the AQI values generated across all formulations are representative of the stated formulations since the great majority of AQI values incorporate all of the individual pollutants.

Table 22. Number (%) of Index calculations based on the number of pollutants missing, Hamilton, 1998-2001

	Number of Pollutants Missing						
	0	**1**	**2**	**3**	**4**	**5**	**6**
AQIEPA	32,354 (92.8)	1,914 (5.49)	354 (1.02)	134 (0.38)	7 (0.02)	33 (0.09)	52 (0.15)
AQIONT	32,469 (93.2)	1,991 (5.71)	167 (0.48)	26 (0.07)	23 (0.07)	172 (0.49)	
HRBI 4p 24hr	32,950 (94.5)	1,653 (4.74)	84 (0.24)	79 (0.23)	82 (0.24)		
HRBI 2p 24hr	33,133 (95.1)	1,627 (4.67)	88 (0.25)				
HRBI 4p 3hr	32,766 (94.0)	1,653 (4.74)	83 (0.24)	66 (0.19)	280 (0.80)		
HRBI 2p 3hr	33,127 (95.1)	1,436 (4.12)	285 (0.82)				
S&T_Hyb	32,950 (94.5)	1,653 (4.74)	84 (0.24)	79 (0.23)	82 (0.24)		
S&T_ONT	32,398 (93.0)	2,086 (5.99)	151 (0.43)	28 (0.08)	126 (0.36)	59 (0.17)	

Table 23. Number (%) of Index calculations based on the number of pollutants missing, Toronto, 1998 and 2001

	Number of Pollutants Missing						
	0	**1**	**2**	**3**	**4**	**5**	**6**
AQIEPA	16,369 (94.1)	630 (3.62)	110 (0.63)	180 (1.03)	12 (0.07)	33 (0.19)	66 (0.38)
AQIONT	16,516 (94.9)	566 (3.25)	154 (0.89)	18 (0.10)	21 (0.12)	125 (0.72)	
HRBI 4p 24hr	16,502 (94.8)	691 (3.97)	24 (0.14)	82 (0.47)	101 (0.58)		
HRBI 2p 24hr	16,785 (96.5)	499 (2.87)	116 (0.67)				
HRBI 4p 3hr	16,299 (93.7)	696 (4.00)	159(0.91)	77 (0.44)	169 (0.97)		
HRBI 2p 3hr	16,620 (95.5)	606 (3.48)	174 (1.00)				
S&T_Hyb	16,502 (94.8)	691 (3.97)	24 (0.14)	82 (0.47)	101 (0.58)		
S&T_ONT	16,514 (94.9)	581 (3.34)	134 (0.77)	26 (0.15)	76 (0.44)	69 (0.40)	

Table 24. Number (%) of Index calculations based on the number of pollutants missing, Ottawa, 1998-2001

	Number of Pollutants Missing						
	0	**1**	**2**	**3**	**4**	**5**	**6**
AQIEPA	30,953 (88.9)	2,664 (7.65)	387 (1.11)	704 (2.02)	38 (0.11)	43 (0.12)	35 (0.10)
AQIONT	30,946 (88.9)	2,706 (7.77)	591 (1.70)	63 (0.18)	291 (0.84)	227 (0.65)	
HRBI 4p 24hr	31,376 (90.1)	2,662 (7.64)	622 (1.79)	106 (0.30)	58 (0.17)		
HRBI 2p 24hr	31,631 (90.8)	3,042 (8.74)	151 (0.43)				
HRBI 4p 3hr	30,206 (86.7)	2904 (8.34)	592 (1.70)	748 (2.15)	374 (1.07)		
HRBI 2p 3hr	31,012 (89.0)	3,374 (9.69)	438 (1.26)				
S&T_Hyb	31,376 (90.1)	2,662 (7.64)	622 (1.79)	106 (0.30)	58 (0.17)		
S&T_ONT	30,973 (88.9)	2,650 (7.61)	631 (1.81)	53 (0.15)	436 (1.25)	81 (0.23)	

Table 25. Number (%) of Index calculations based on the number of pollutants missing, Windsor, 2001

	Number of Pollutants Missing						
	0	**1**	**2**	**3**	**4**	**5**	**6**
AQIEPA	7,853 (89.6)	808 (9.22)	39 (0.45)	37 (0.42)	0	10 (0.11)	13 (0.15)
AQIONT	7,939 (90.6)	738 (8.42)	9 (0.10)	3 (0.03)	15 (0.17)	56 (0.64)	
HRBI 4p 24hr	8101 (92.5)	589 (6.72)	23 (0.26)	24 (0.27)	23 (0.26)		
HRBI 2p 24hr	8215 (93.8)	520 (5.94)	25 (0.29)				
HRBI 4p 3hr	8,112 (92.6)	503 (5.74)	5 (0.06)	37 (0.42)	103 (1.18)		
HRBI 2p 3hr	8,219 (93.8)	437 (4.99)	104 (1.19)				
S&T_Hyb	8,101 (92.5)	589 (6.72)	23 (0.26)	24 (0.27)	23 (0.26)		
S&T_ONT	7,880 (89.9)	802 (9.16)	7 (0.08)	4 (0.05)	52 (0.59)	15 (0.17)	

Plots of hourly changes in AQI values for each of the AQI formulations

Hamilton

The hourly changes in AQI values for each formulation using air pollution data from the Hamilton site are presented in Figures 3a to 3h. From the AQIEPA and AQIONT formulation distribution plots, it is shown that the great majority of hours are associated with AQI values below their respective unhealthy or poor air quality designations. A distinct pattern is also observed over time with defined low and high periods. This is specifically linked to seasonal variations with lower values found during the winter months and higher values associated with the summer months. This seasonal pattern is observed across formulations and results in 4 distinct summer month peaks.

Upon examination of the HRBI formulations, the greatest range of values is observed in the HRBI 4p 3hr formulation. This formulation results in hours with very low AQI values, consistent across all HRBI formulations, but has the largest peak values. Although, the HRBI 4p 24hr formulation appears to have consistently higher values, the largest peak values are associated with the HRBI 4p 3hr formulation. In addition, the HRBI 2p formulations have consistently lower values than the HRBI 4p formulations showing the influence of NO_2 and SO_2 on the overall AQI values. The S&T_Hyb formulation has lower peak values when compared to the HRBI formulations; however, there are only few values below an AQI value of one. In the comparison of the S&T_ONT to the AQIONT formulation, higher values are observed with the S&T_ONT along with a larger overall range of values. This shows that the S&T_ONT is increasingly sensitive to increasing pollutant concentrations.

Figure 3a

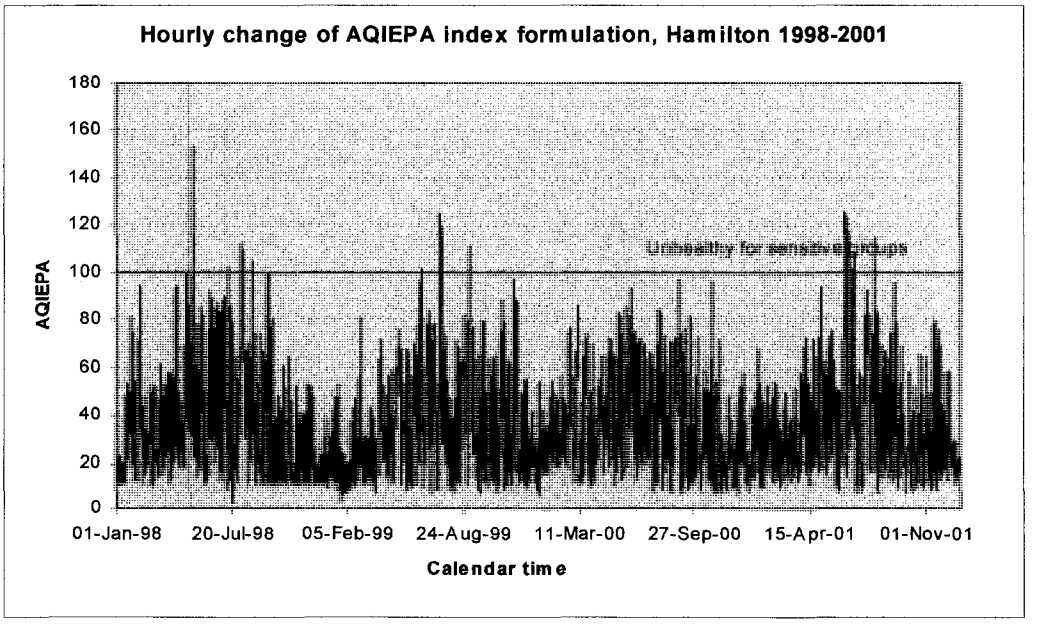


Figure 3b

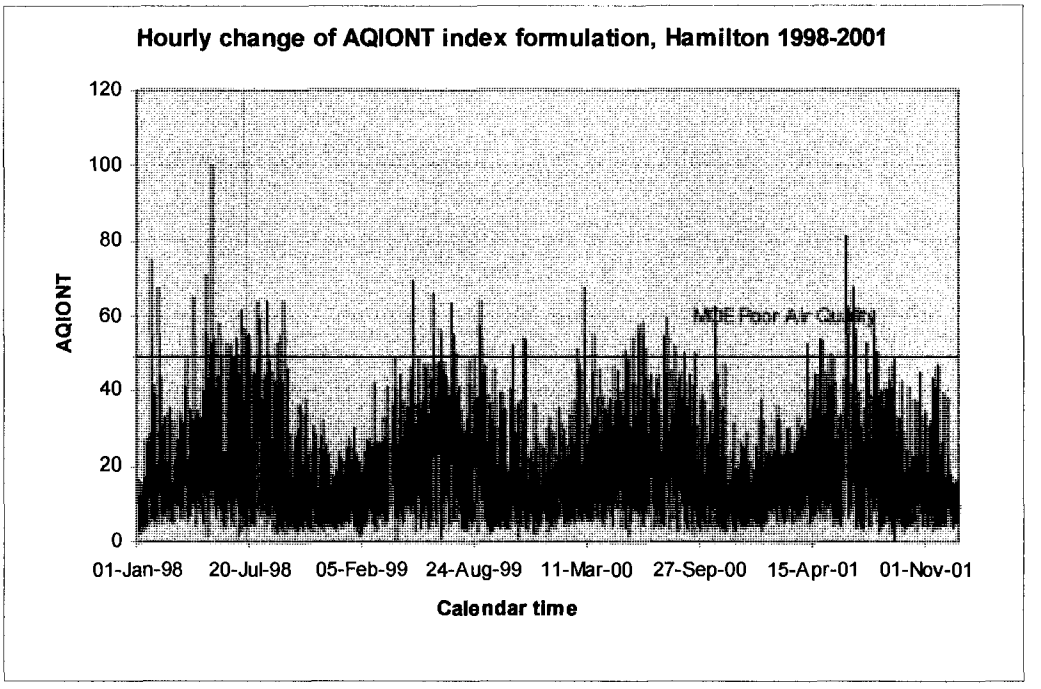


Figure 3c

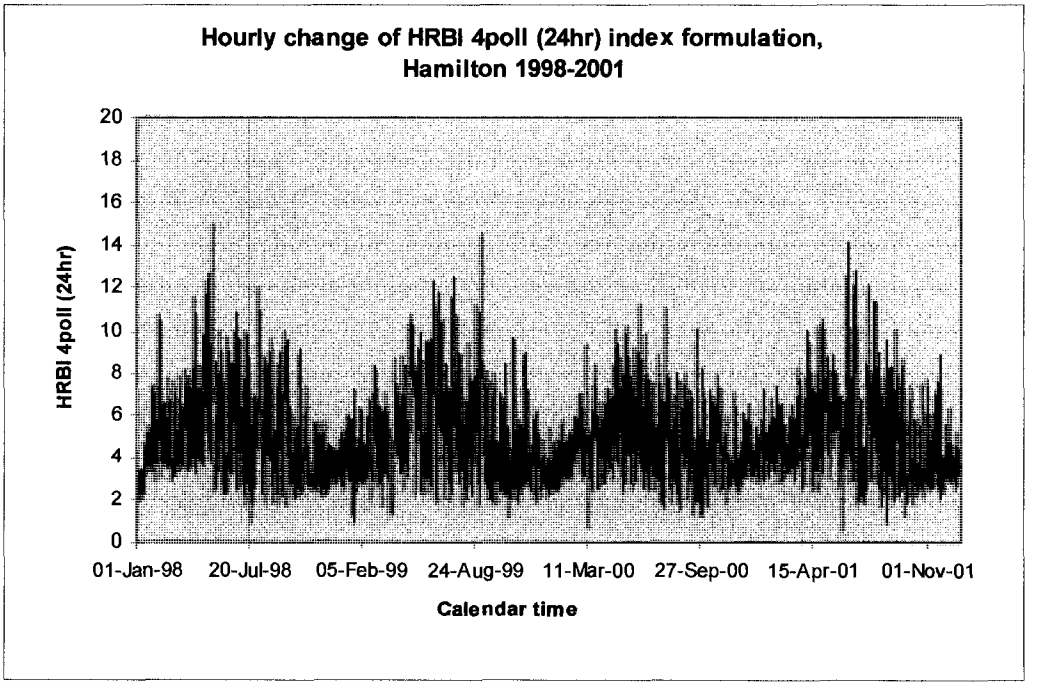


Figure 3d

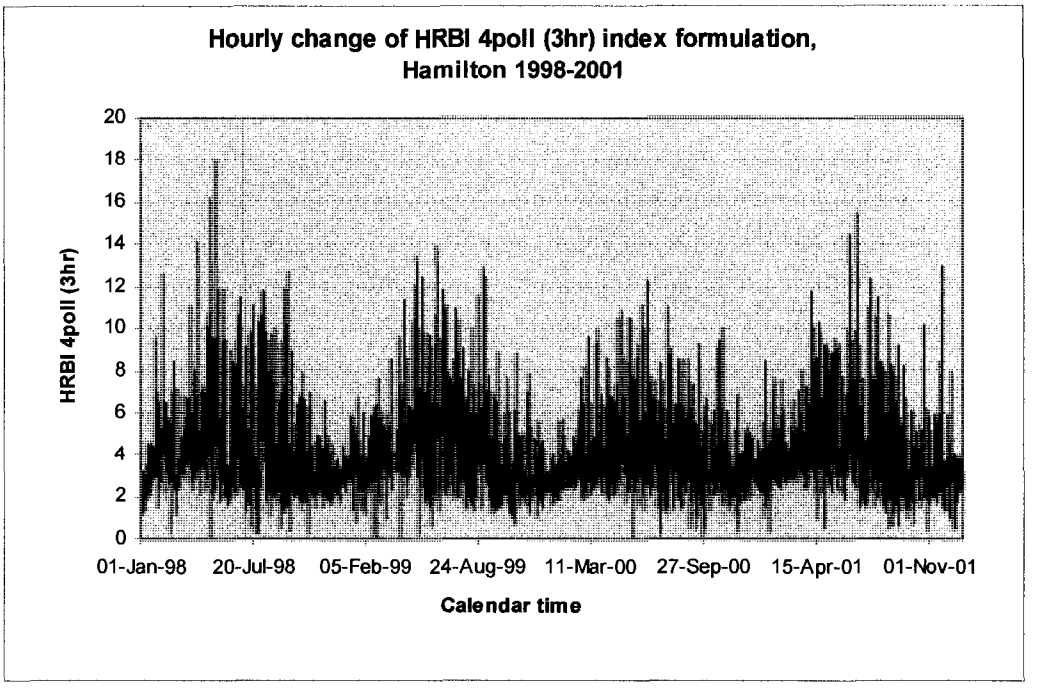


Figure 3e

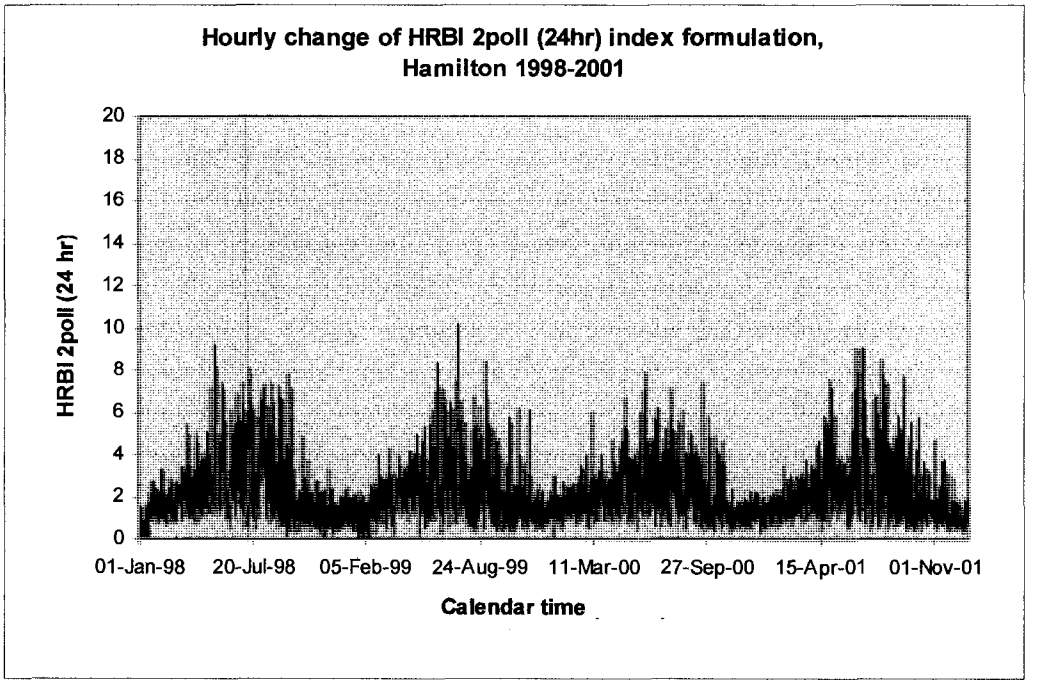


Figure 3f

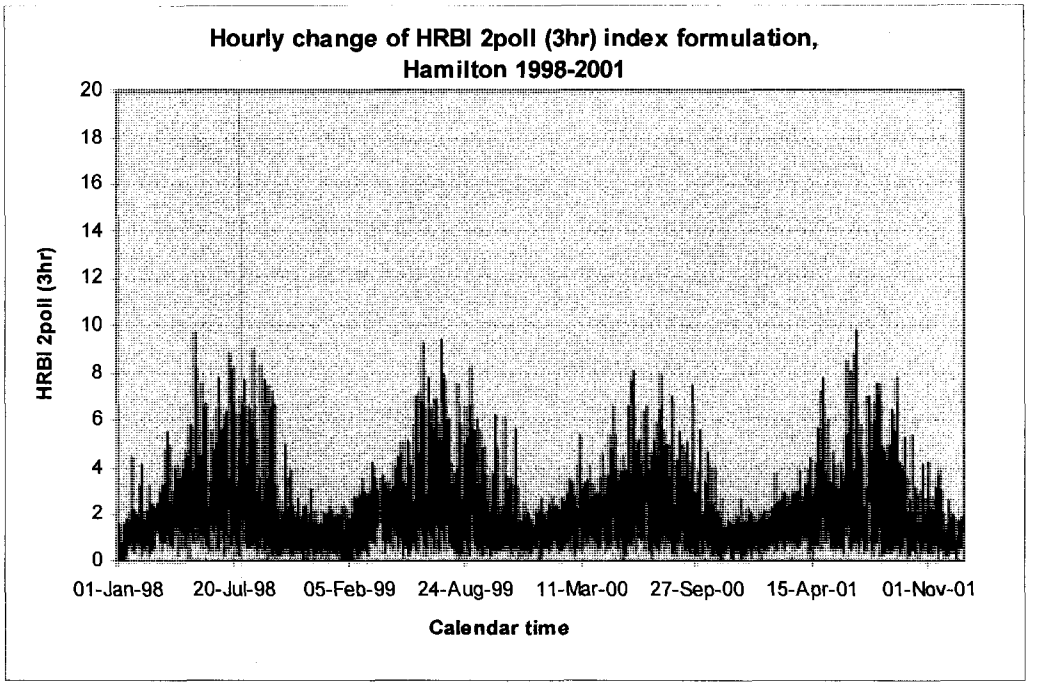


Figure 3g

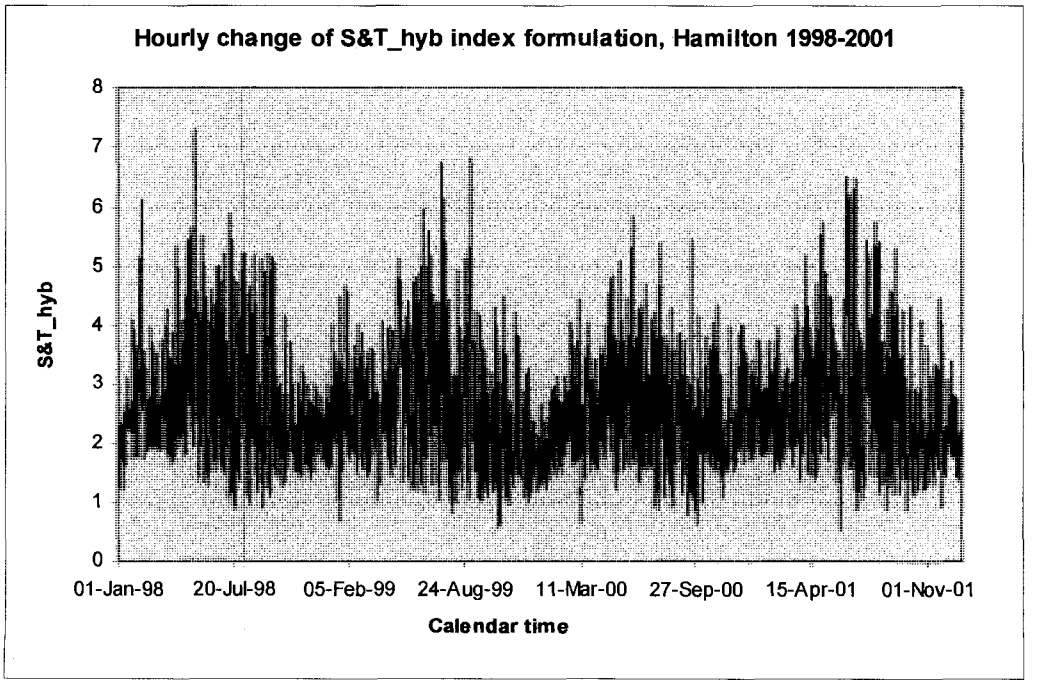
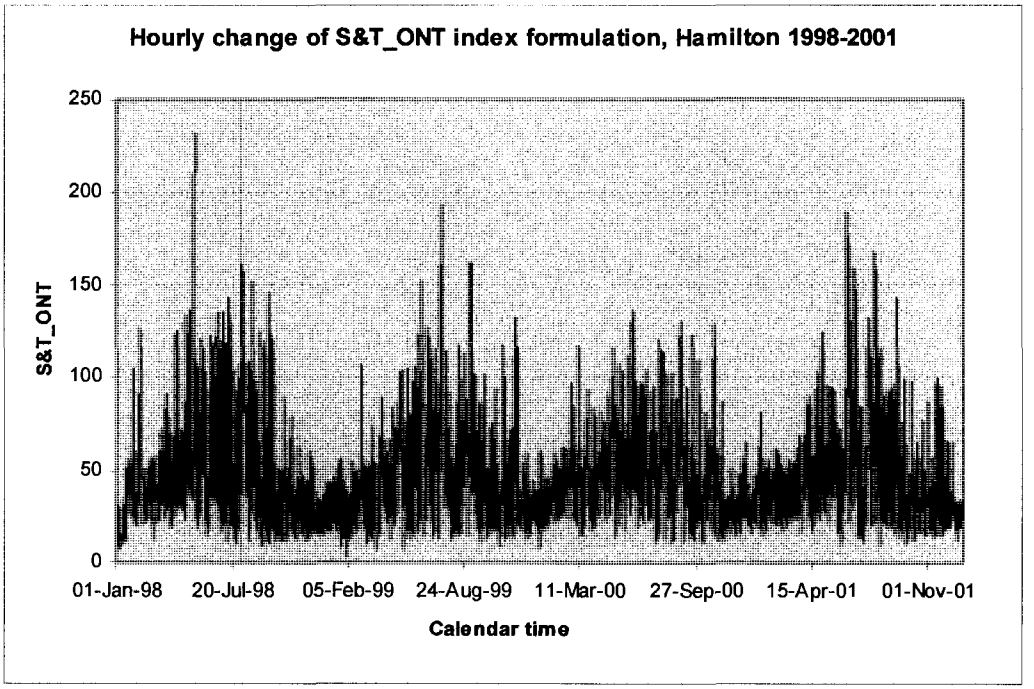


Figure 3h



Toronto

A similar pattern of values is observed across the plots of the hourly change in AQI values for the Toronto site data (Figures 4a to 4h). The Toronto site data consist only of two years, thus only two distinct seasonal peaks are observed. The peak values across all formulations are not as high as those observed using the Hamilton dataset.

Figure 4a

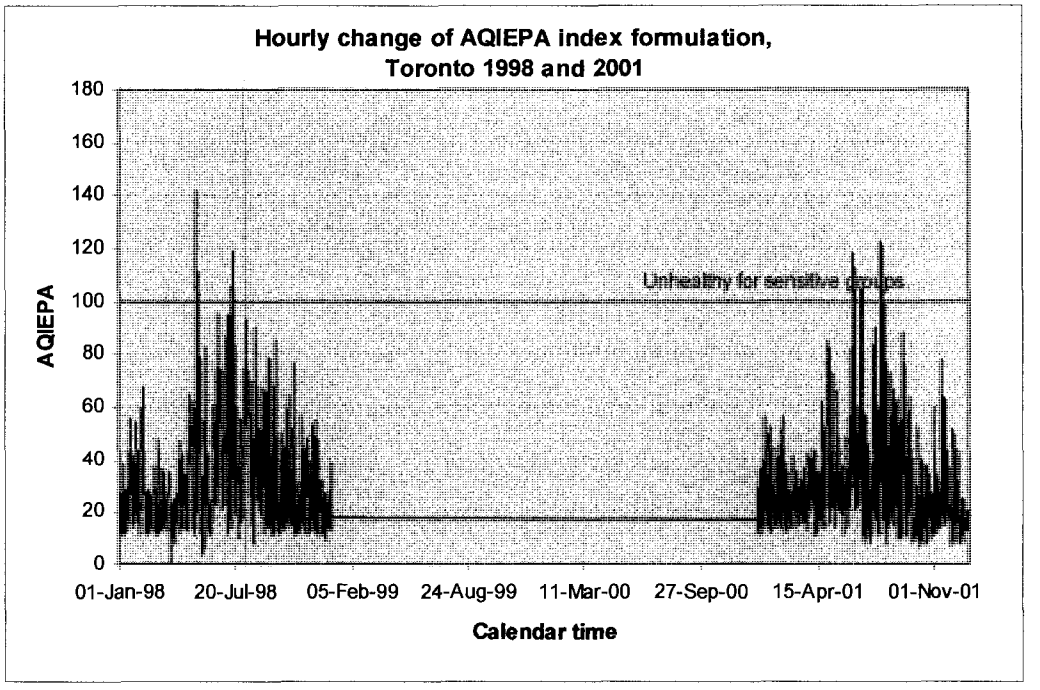


Figure 4b

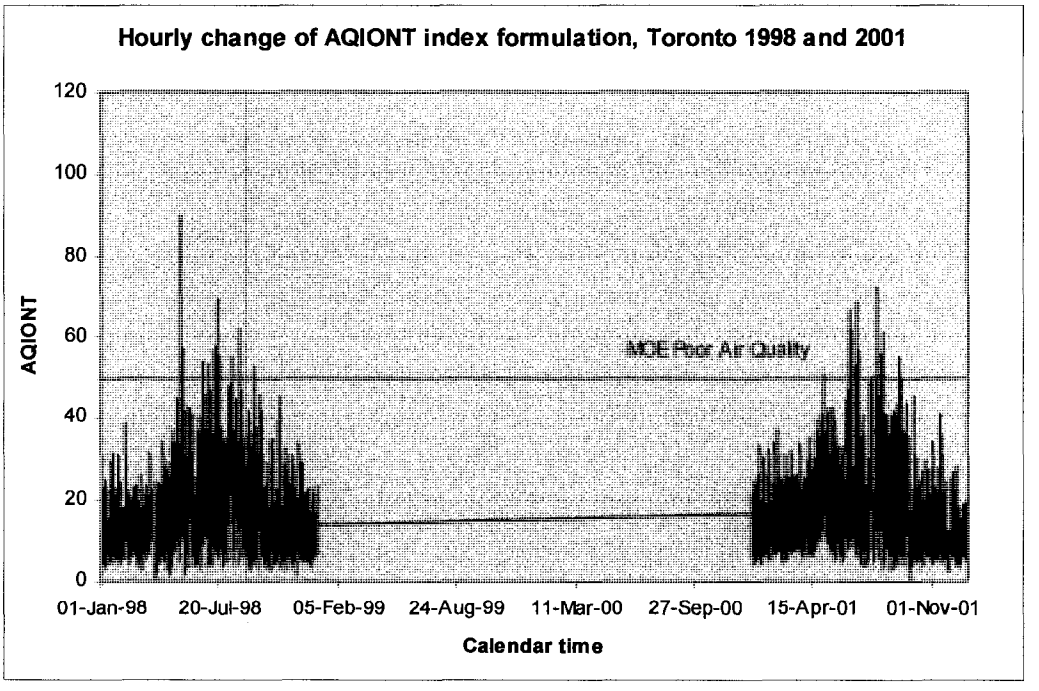


Figure 4c

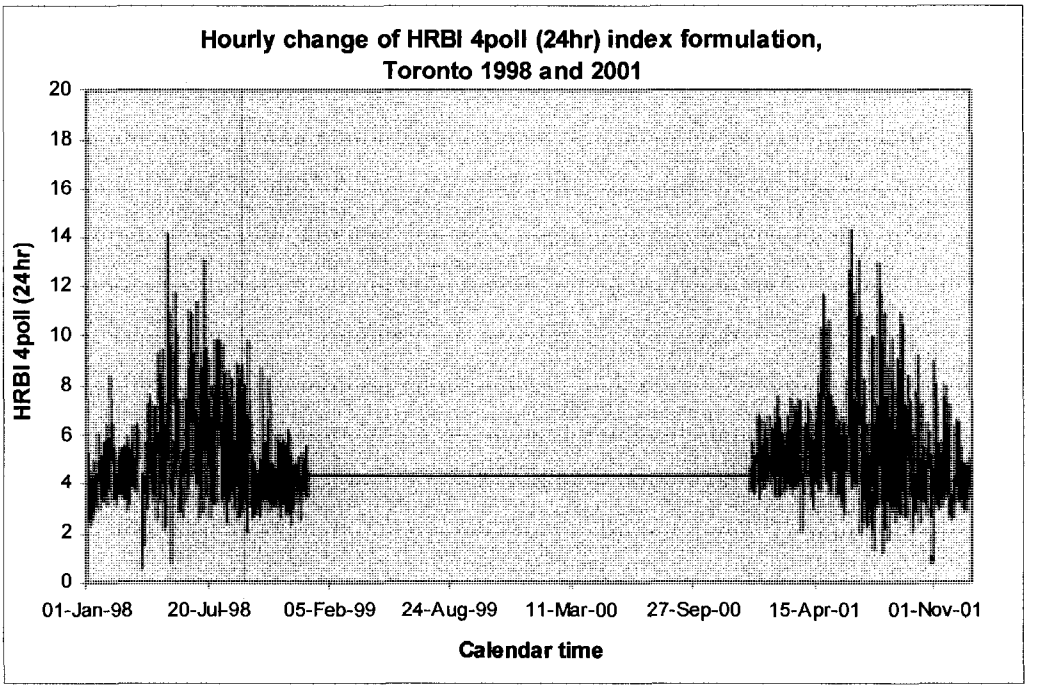


Figure 4d

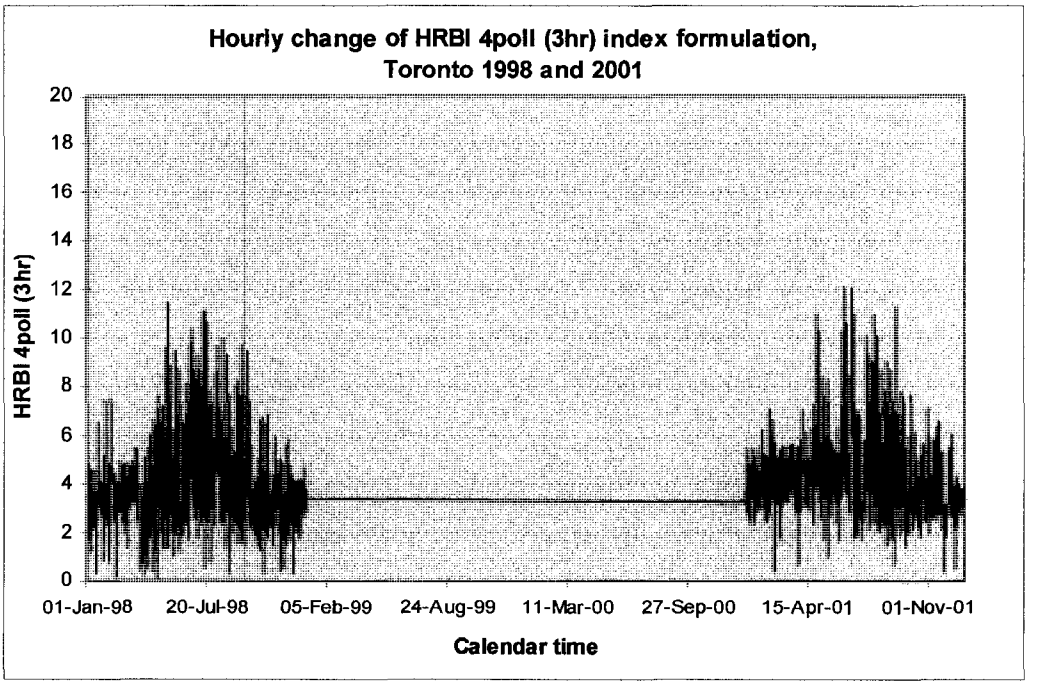


Figure 4e

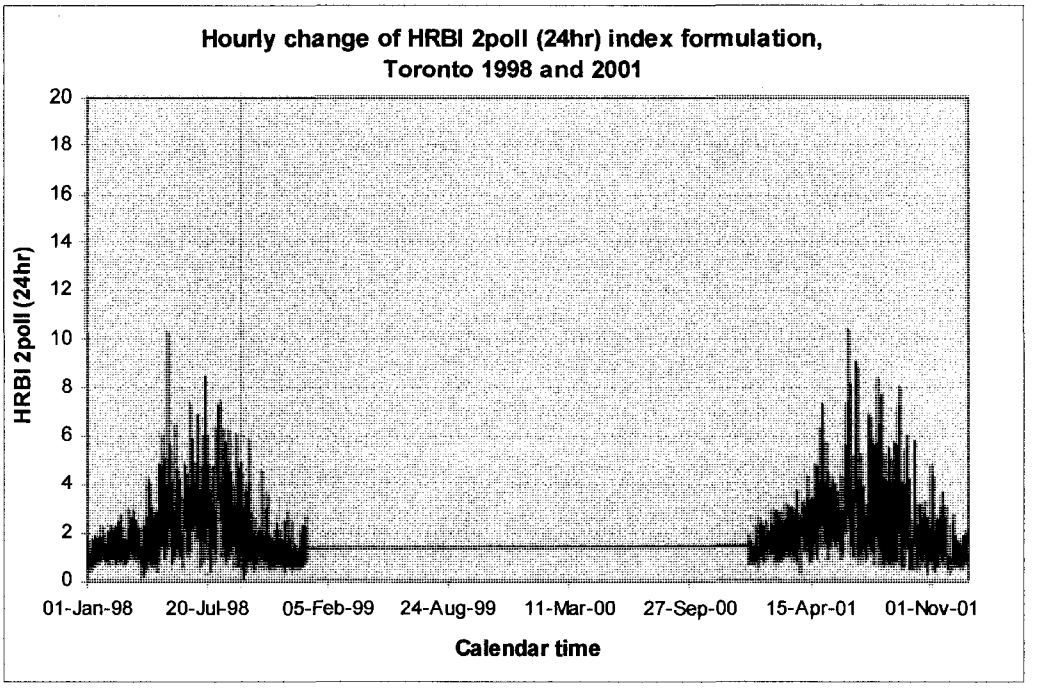


Figure 4f

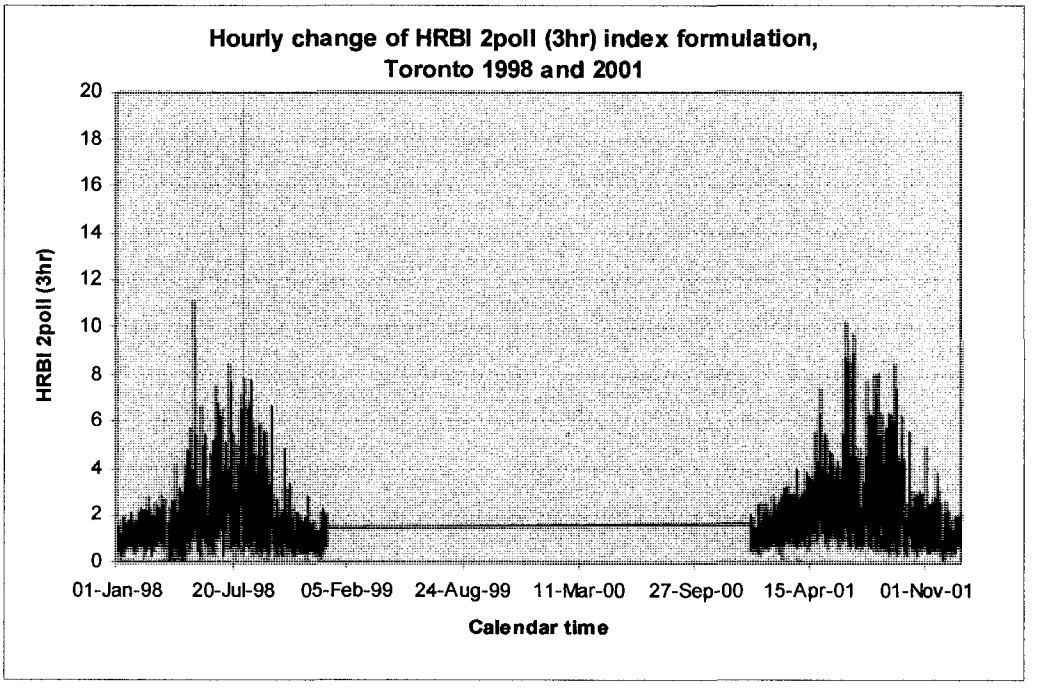


Figure 4g

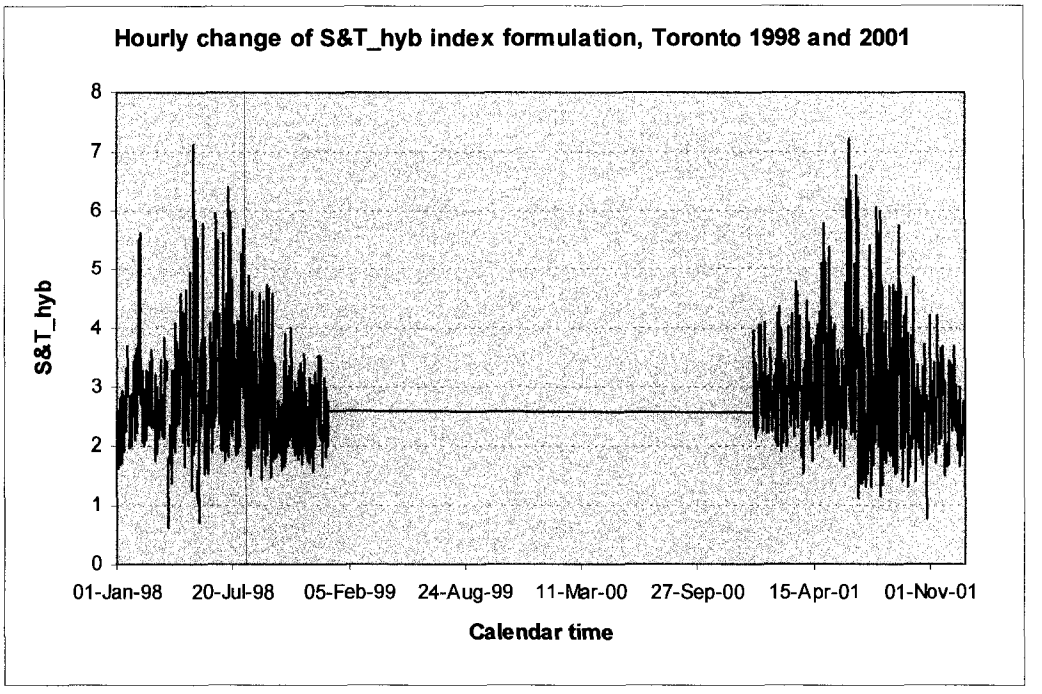
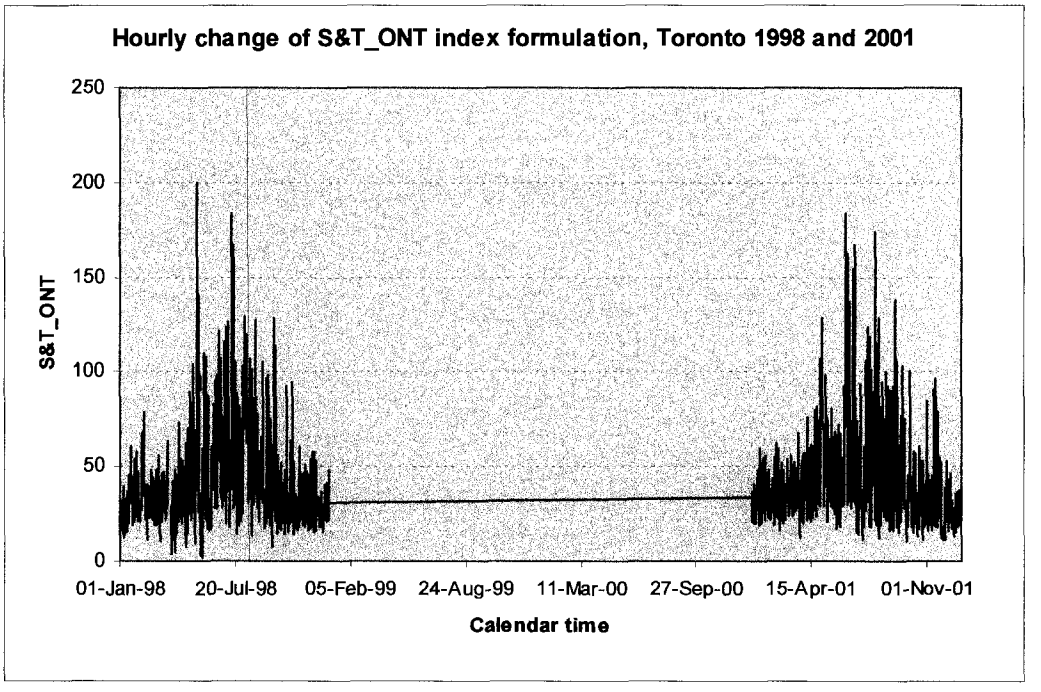


Figure 4h



Ottawa

Using the Ottawa site pollutant data, four peaks are also observed representing the four years worth of data; although the peaks are not as distinct across the different formulations (Figures 5a to 5h). It is particularly difficult to distinguish these peaks using the HRBI 4p 3hr formulation in comparison to the other HRBI formulations. This is also the case for the other non-HRBI formulations. Upon examination of some of the peak values, there appear to be some notable differences across the formulations. Around the end of January 1999 there is a notably high AQI value observed with the HRBI 4p 3hr formulation, whereas there is no comparable peak using either of the HRBI 2p formulations. Comparable peaks are observed using the AQIEPA and AQIONT suggesting that there is a pollutant driver for this peak and it is neither $PM_{2.5}$ nor O_3, since we do not see any comparable peaks with the HRBI 2p formulations. A detailed investigation of this peak is presented as part of Questions *3. What are the pollutant concentrations underlying 'high/poor' air quality index values and outlier values?* Furthermore, the plots also show that the Ottawa site data have lower overall AQI values when compared to the other Ontario sites.

Figure 5a

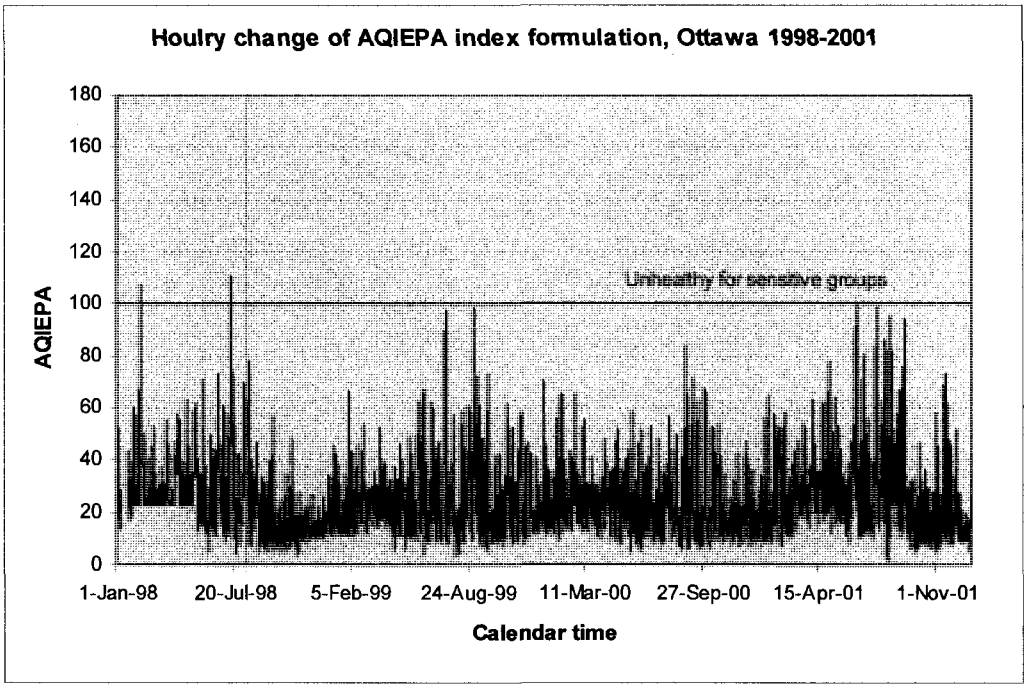


Figure 5b

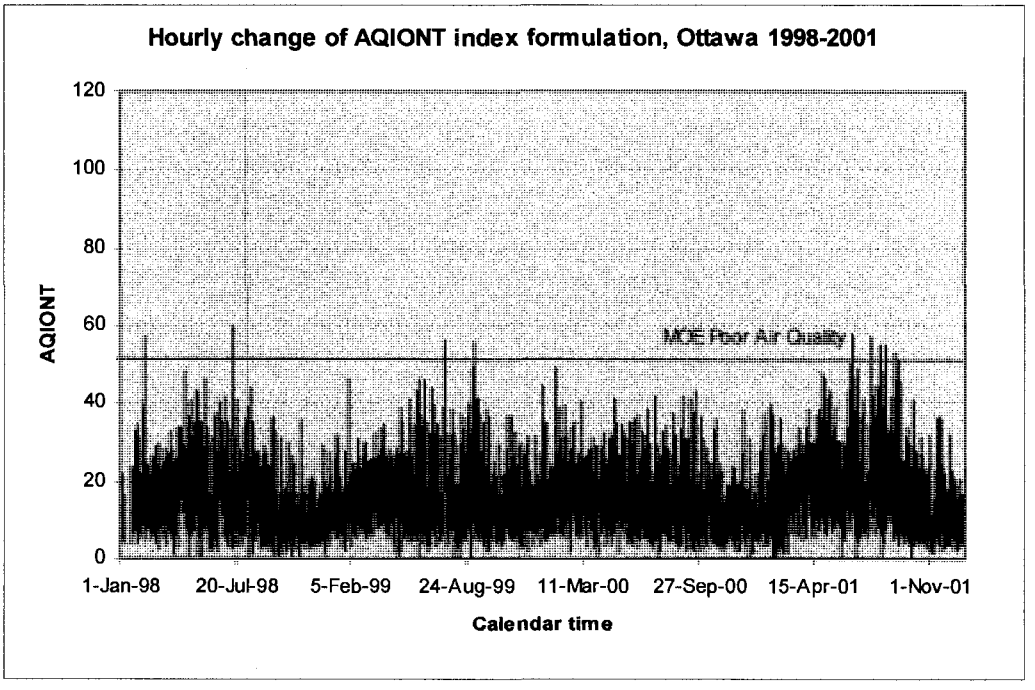


Figure 5c

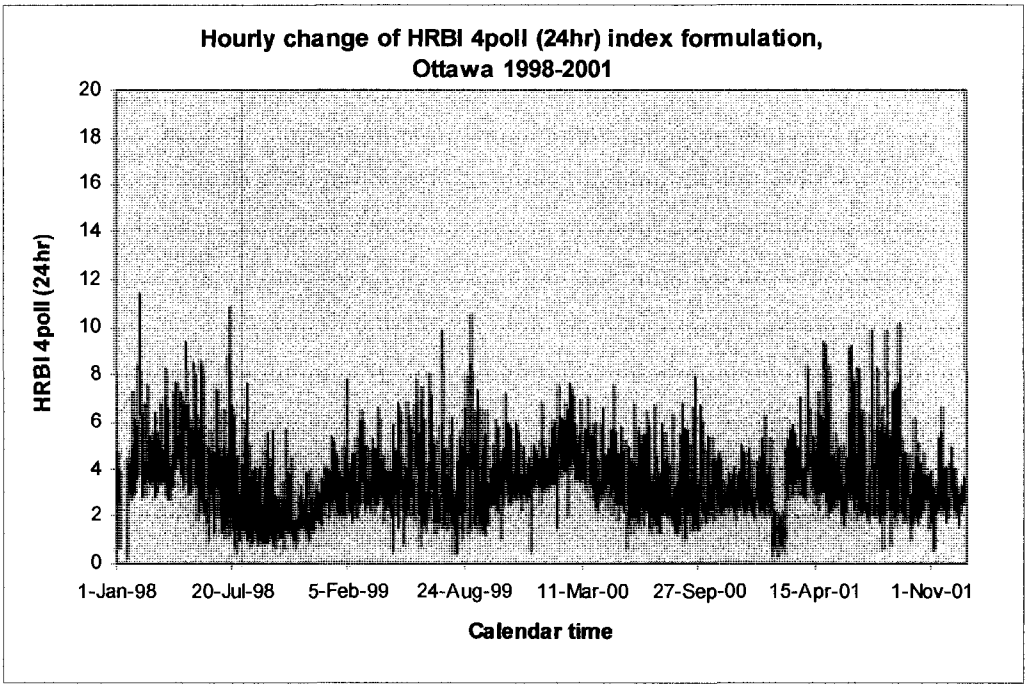


Figure 5d

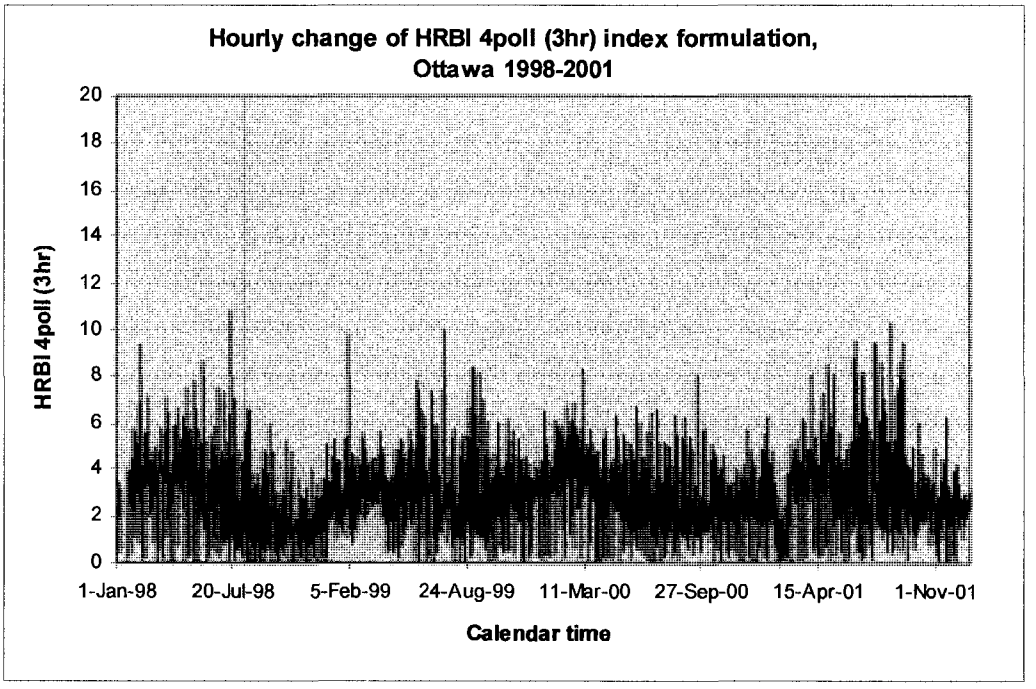


Figure 5e

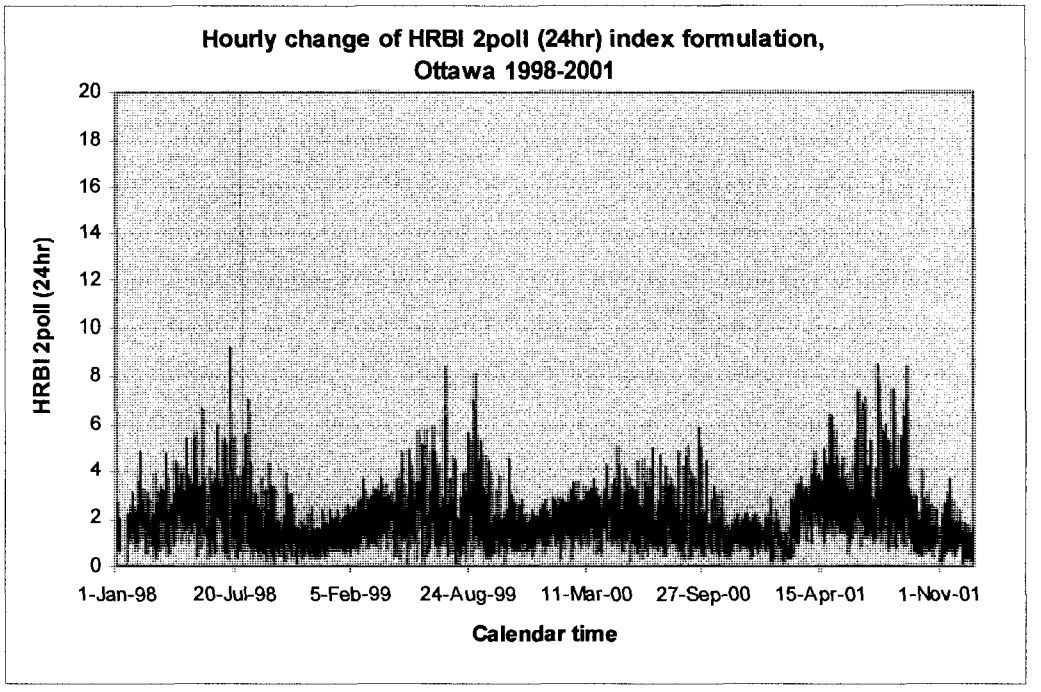


Figure 5f

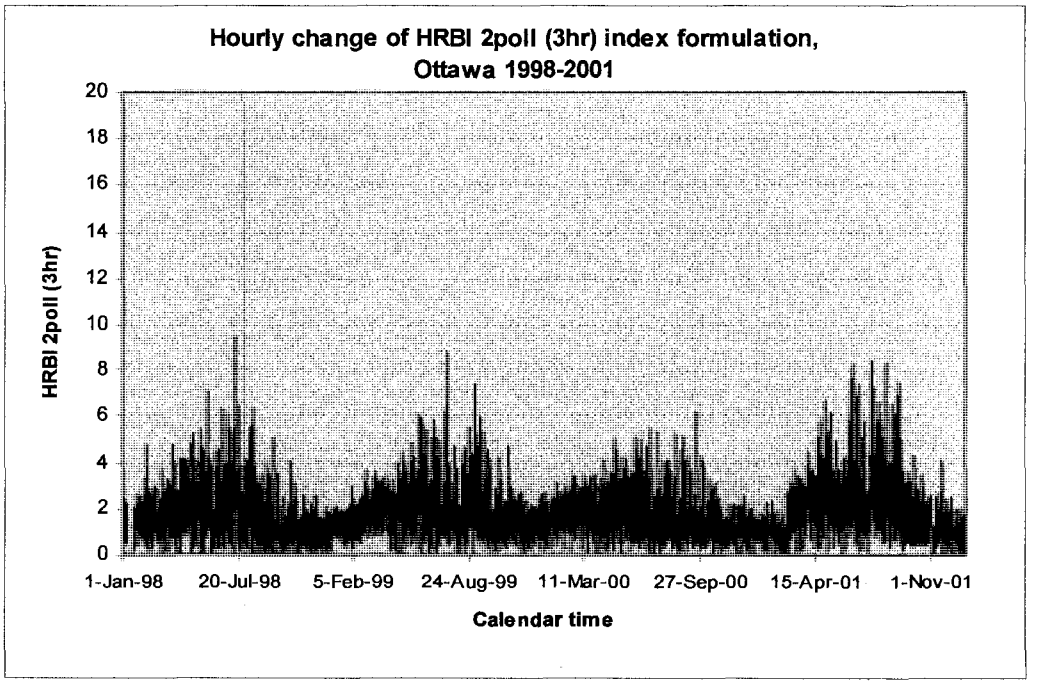


Figure 5g

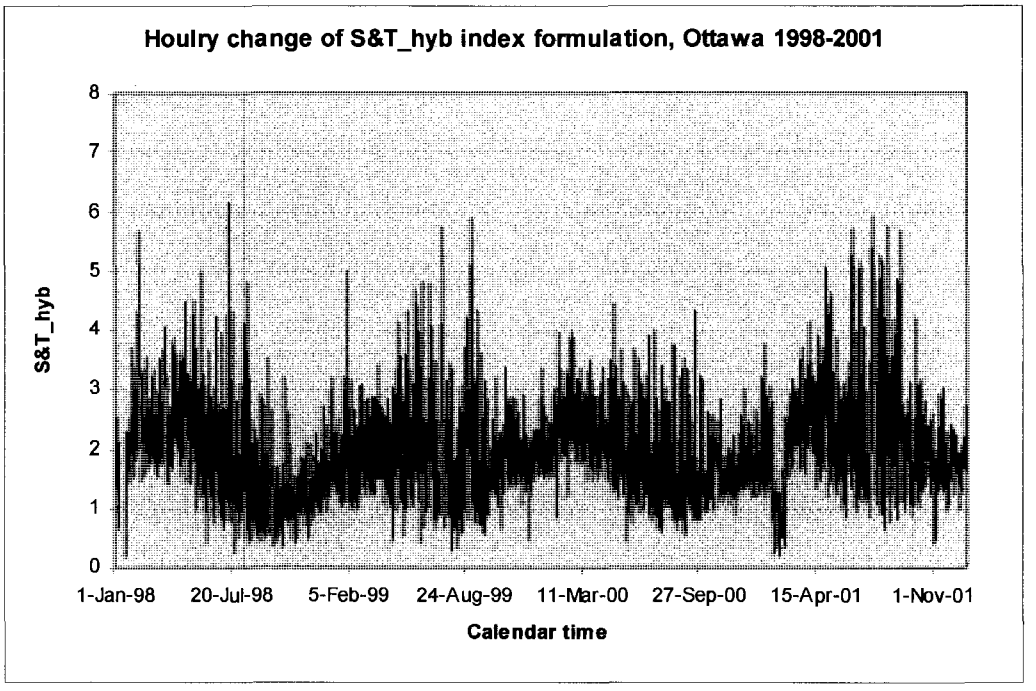
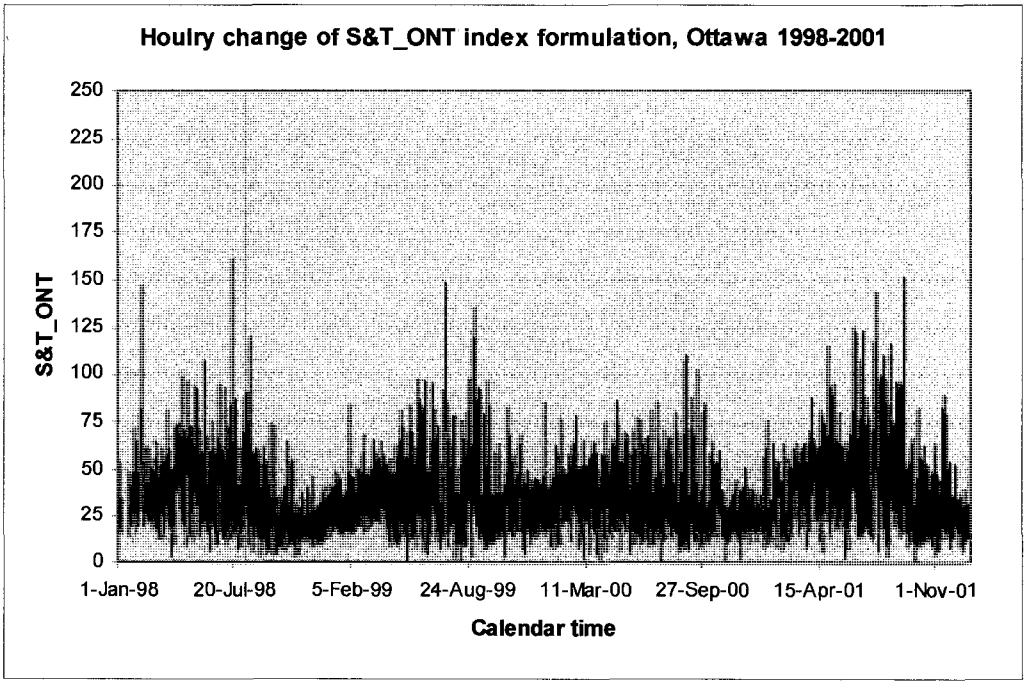


Figure 5h



Windsor

The plots of hourly AQI value changes using the Windsor site data represent one year's worth of data. A larger peak of values is observed between June and July; however the majority of the formulations also show another peak of values around the beginning of May 2001 (Figures 6a to 6h). Since the Windsor data set consists of only year's worth of data it is easier to observe these additional peaks across the year. It also appears that there is a lower range of values for the Windsor site in comparison to Hamilton except with the HRBI 2p formulations. This suggests that $PM_{2.5}$ and O_3 pollutant concentrations tend to be more problematic in Windsor than in Hamilton. Upon examination of the S&T formulations, the S&T_Hyb formulation has notably lower AQI values in comparison to the HRBI formulations. On the other hand, the S&T_ONT formulation has larger AQI values and a larger range of values in comparison to the AQIONT.

Figure 6a

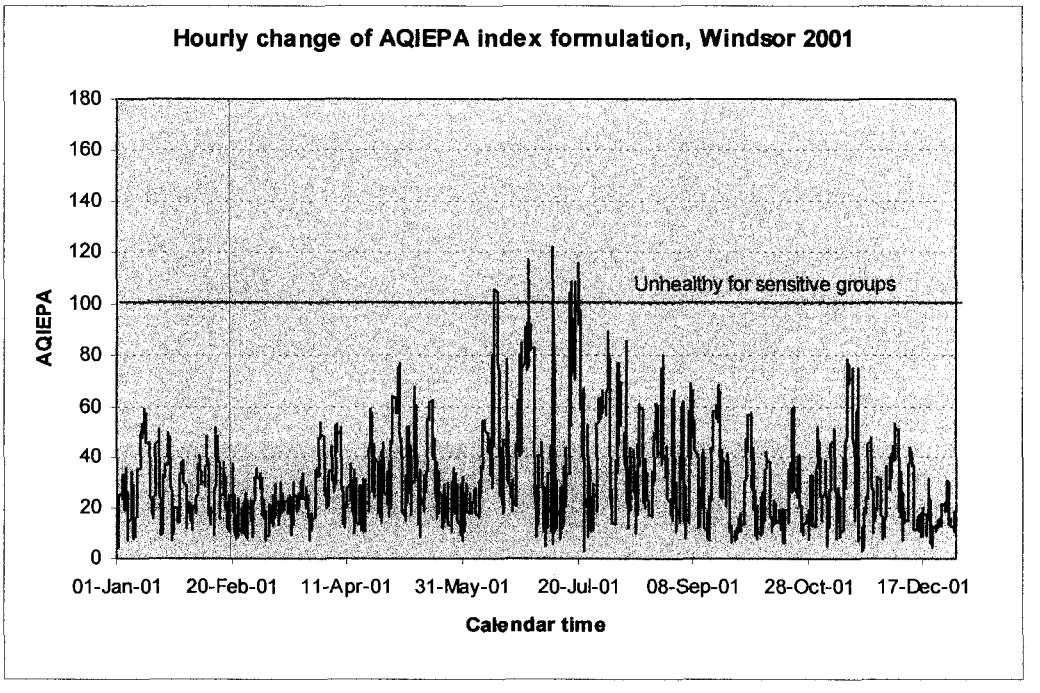


Figure 6b

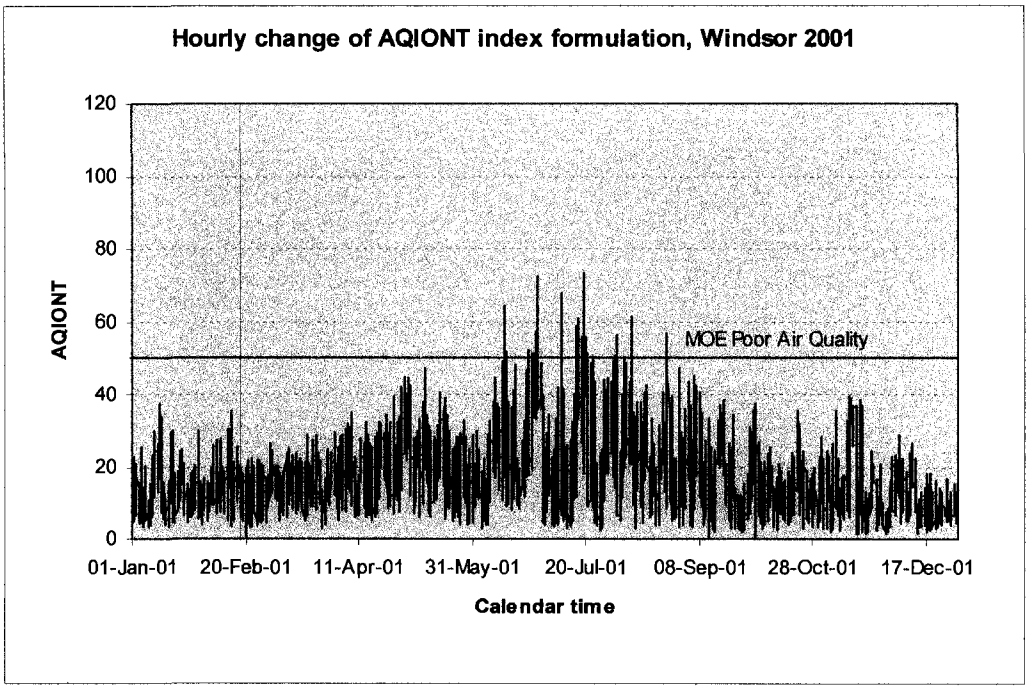


Figure 6c

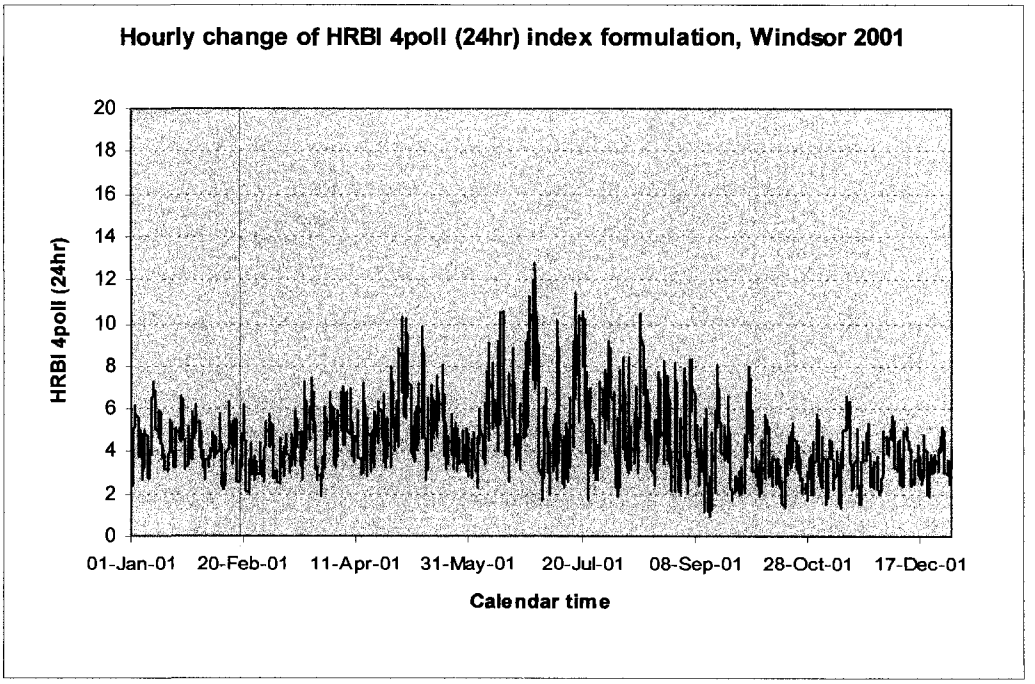


Figure 6d

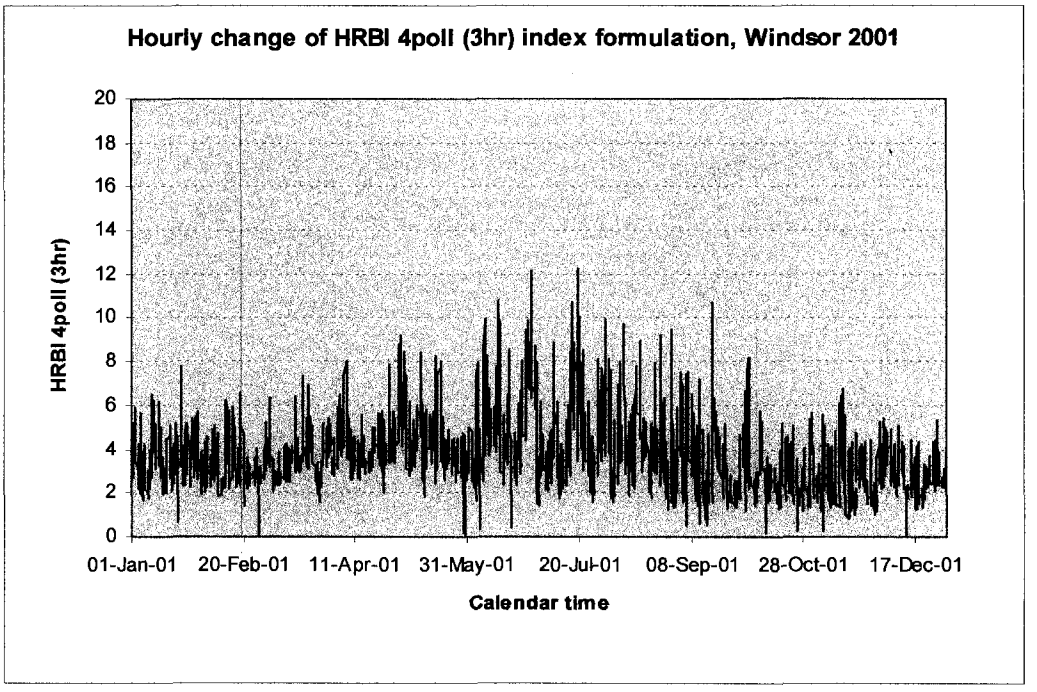


Figure 6e

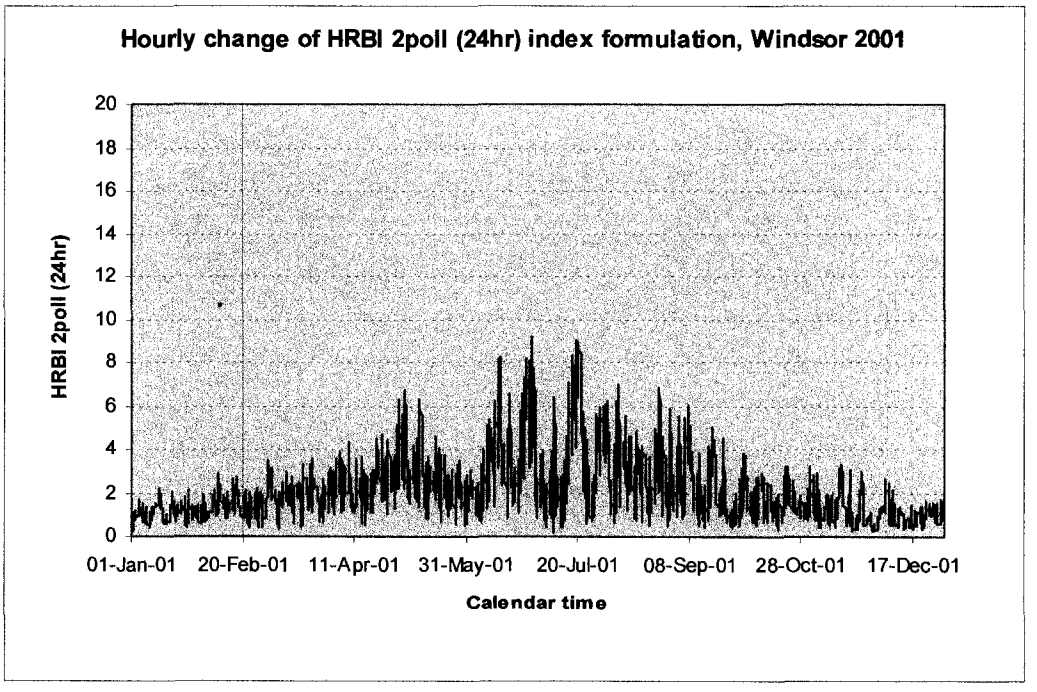


Figure 6f

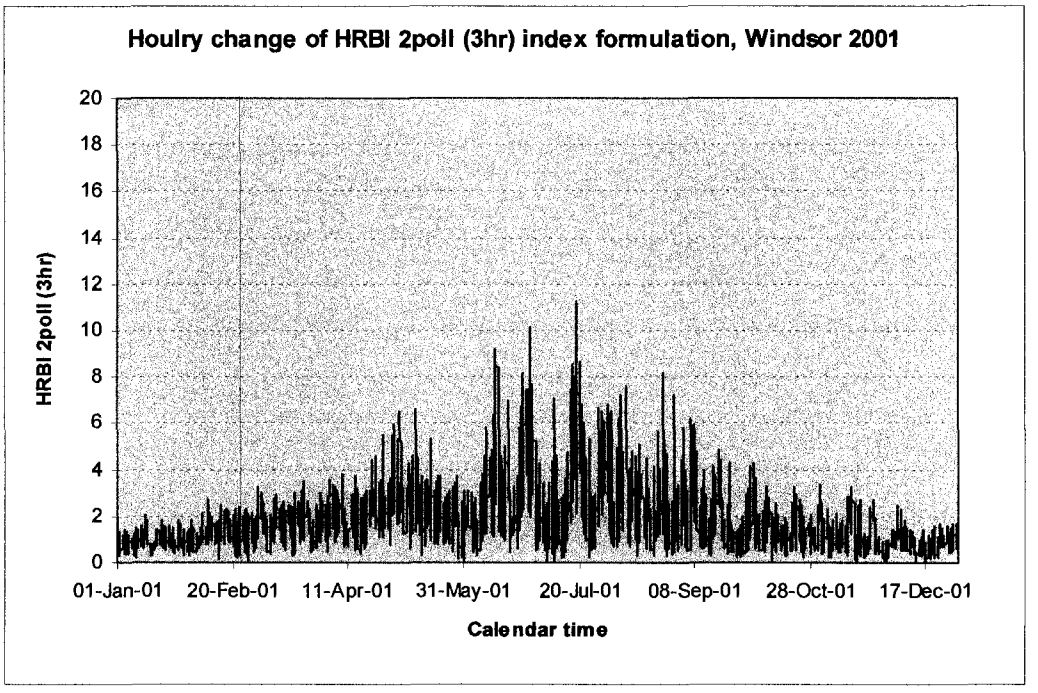


Figure 6g

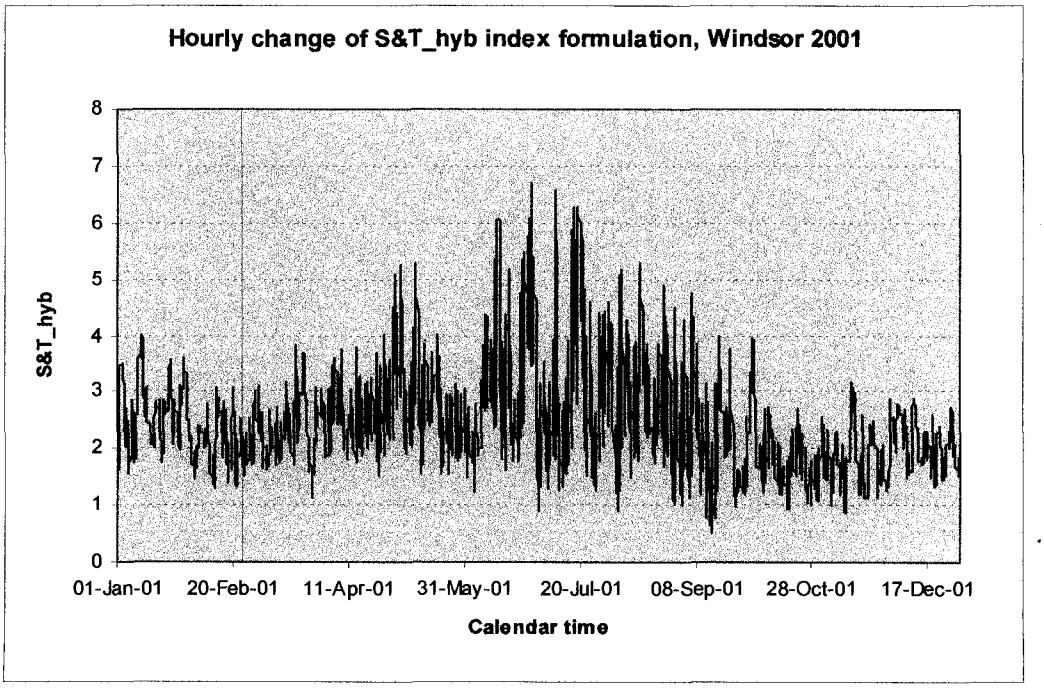
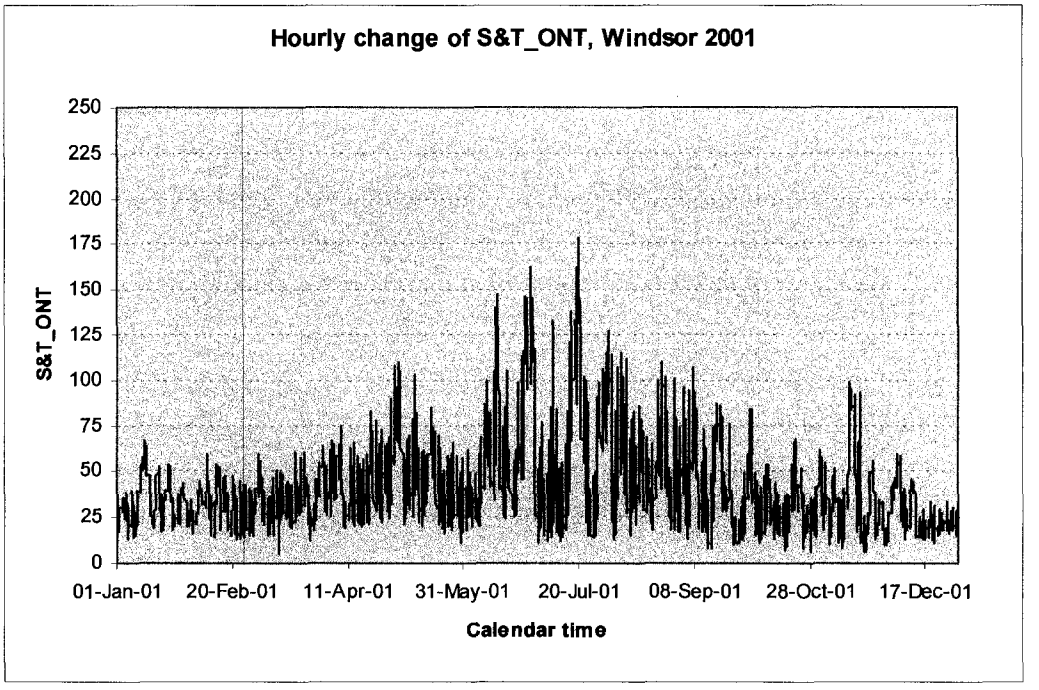


Figure 6h



All of the above plots were used to help identify peak AQI values or "outlier" AQI values for comparison across the different formulations when peaks were not consistently observed across the formulations. The results of this inquiry are summarized under Question 3.

Percent distribution of AQI value categories for each of the AQI formulations

Using the established categories for the AQIONT and AQIEPA, the percent distribution of AQI values within these categorizations was assessed. The distribution of AQI values for the HRBI formulations were categorized into 10 categories reflecting the unit increase in AQI values of the 0-10+ scale. This classification was also used for the S&T_Hyb formulation. For comparability, the S&T_ONT formulation results were categorized using the AQIONT classification. The results are summarized in Tables 26

to 30. Following the tables, a short descriptive summary for each site is presented with accompanying figures.

Table 26. Percent Distribution of hours by AQI categories for Selected Ontario Monitoring Sites, AQIEPA

	0-50	51-100	101-150	151-200	201-300	301-400	401-500+
Hamilton	76.58	22.82	0.57	0.03	0	0	0
Toronto	85.12	14.20	0.69	0	0	0	0
Ottawa	92.71	7.17	0.12	0	0	0	0
Windsor	84.96	14.55	0.49	0	0	0	0

Table 27. Percent Distribution of hours by AQI categories for Selected Ontario Monitoring Sites, AQIONT

	0-15	16-31	32-49	50-99	100+
Hamilton	43.88	41.52	13.41	1.18	0.003
Toronto	49.15	39.94	9.96	0.94	0
Ottawa	49.89	44.31	5.60	0.19	0
Windsor	45.63	42.34	10.90	1.13	0

Table 28. Percent Distribution of hours by AQI categories for Selected Ontario Monitoring Sites, HRBI Formulations

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10+
Hamilton											
HRBI 4p 24hr	0.07	1.37	12.85	25.14	23.05	14.69	10.09	5.94	3.24	1.83	1.74
HRBI 2p 24hr	15.24	39.39	24.35	10.58	5.32	2.85	1.31	0.69	0.19	0.07	0.01
HRBI 4p 3hr	0.32	5.36	28.32	28.93	16.56	9.07	5.12	2.77	1.70	0.94	0.91
HRBI 2p 3hr	23.73	38.85	20.08	8.75	4.42	2.22	1.16	0.60	0.13	0.06	0
Toronto											
HRBI 4p 24hr	0.14	0.25	4.67	22.71	30.32	20.20	10.04	4.91	3.12	1.83	1.80
HRBI 2p 24hr	15.88	43.14	21.56	10.00	4.75	2.40	1.26	0.62	0.30	0.06	0.03
HRBI 4p 3hr	0.45	2.10	18.74	35.55	22.83	9.95	4.51	2.88	1.75	0.71	0.53
HRBI 2p 3hr	25.00	39.77	19.07	8.35	3.78	2.04	1.04	0.67	0.19	0.05	0.03
Ottawa											
HRBI 4p 24hr	1.28	11.23	27.49	29.74	17.13	7.67	3.30	1.21	0.59	0.22	0.15
HRBI 2p 24hr	15.88	42.38	28.12	8.91	2.70	0.96	0.54	0.17	0.07	0.01	0
HRBI 4p 3hr	4.01	18.64	35.04	25.89	10.39	3.66	1.34	0.61	0.29	0.11	0.02
HRBI 2p 3hr	22.48	42.72	23.83	7.08	2.25	0.99	0.42	0.18	0.06	0.01	0
Windsor											
HRBI 4p 24hr	0.06	2.09	15.07	25.80	24.91	16.56	7.51	3.98	1.98	1.11	0.93
HRBI 2p 24hr	18.11	39.24	22.61	10.04	4.83	2.51	1.44	0.76	0.41	0.05	0
HRBI 4p 3hr	0.61	7.90	28.08	23.38	18.29	8.28	3.80	2.59	1.34	0.47	0.25
HRBI 2p 3hr	27.08	36.01	20.07	8.09	3.86	2.26	1.52	0.74	0.25	0.07	0.05

Table 29. Percent Distribution of hours by AQI categories for Selected Ontario Monitoring Sites, S&T_Hyb

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10+
Hamilton	0.48	26.59	46.08	19.57	5.54	1.45	0.26	0.02	0	0	0
Toronto	0.14	11.21	51.63	27.78	6.94	1.95	0.31	0.03	0	0	0
Ottawa	7.39	47.14	37.12	6.49	1.41	0.43	0.01	0	0	0	0
Windsor	0.70	30.89	48.96	14.49	3.31	1.37	0.27	0	0	0	0

Table 30. Percent Distribution of hours by AQI categories for Selected Ontario Monitoring Sites, S&T_ONT

	0-15	16-31	32-49	50-99	100+
Hamilton	2.15	29.32	32.79	30.23	5.50
Toronto	1.01	35.04	36.03	23.51	4.41
Ottawa	6.57	37.59	35.87	18.67	1.30
Windsor	3.75	33.79	32.51	25.67	4.28

Hamilton

Figures 7a to 7i represent the percent distribution of AQI value categories using the different AQI formulations for the Hamilton dataset. The AQIONT and AQIEPA formulations classified over 80 percent and 70 percent of the AQI values respectively, as either very good or good air quality. As for the distribution of values in other categories, the AQIONT has AQI values distributed across 4 categories where a maximum of 5 defined categorizations exist, while the AQIEPA only has AQI values classified to 3 categories even though there are up to seven defined categories. The AQIONT has a slightly higher percentage of AQI values classified as poor air quality as compared to the AQIEPA but in both cases these values represent less than five percent of all the AQI values. With the HRBI formulations a different distributional picture is observed, with less skewness of results to the right. However, the HRBI 2p formulations show greater skewness to the right than the 4p formulations with the majority of AQI values distributed at the very low levels on the 0-10+ scale. The different averaging times for

the HRBI 2p formulations do not result in any noticeable differences for the classification of moderate to high level AQI values using the Hamilton dataset. The HRBI 4p 24hr formulation is skewed the least with the greatest percentage of AQI values classified to higher levels than the other HRBI formulations. It is obvious that the HRBI formulations have a greater percentage of AQI values classified to higher levels than the AQIONT or AQIEPA formulations. The percent distribution of values for the S&T_Hyb formulation is also skewed to the right although there are no AQI values larger than 8. Using the S&T_ONT formulation, there is a fairly even split of values between the 3 classifications of: 16-31, 32-49 and 50-99. However, it is important to note that this classification of may not be applicable to this new formulation. Still, it is interesting to observe the percent distribution of values using the S&T_ONT formulation if AQIONT categorizations are used.

Figure 7a

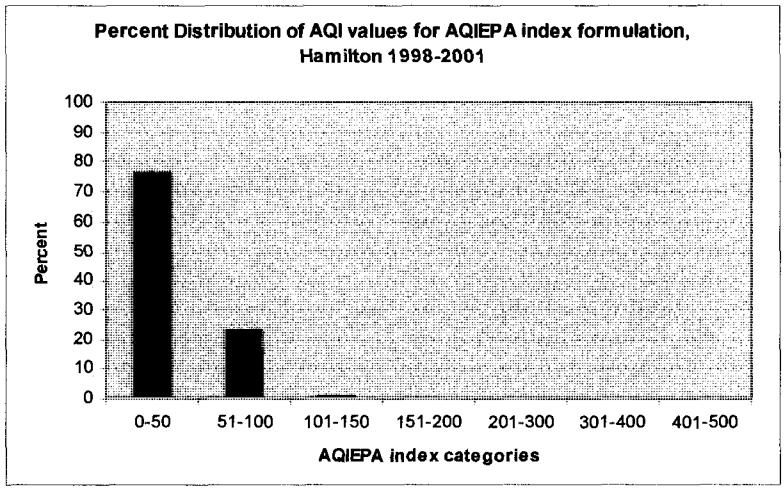


Figure 7b

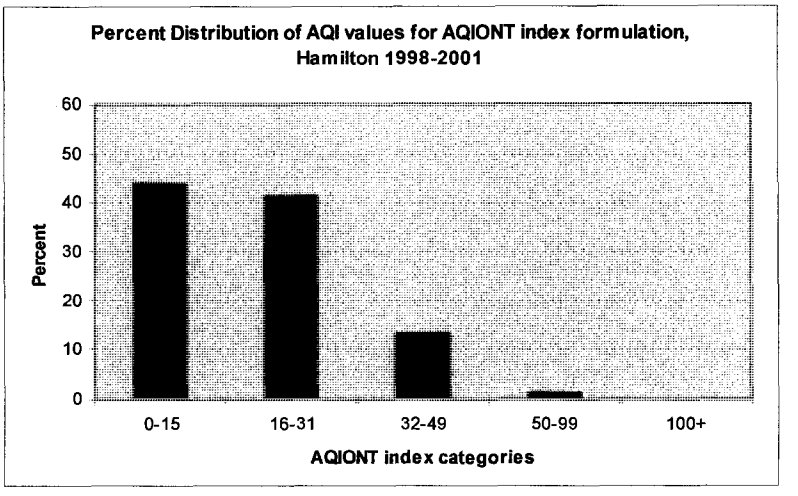


Figure 7c

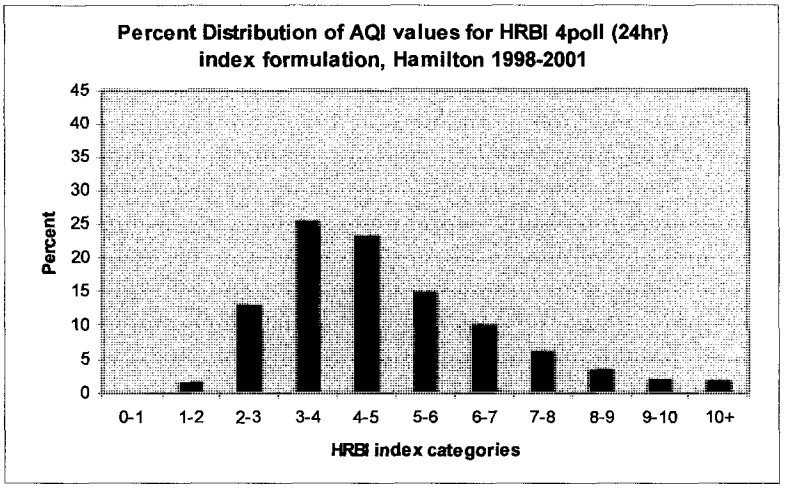


Figure 7d

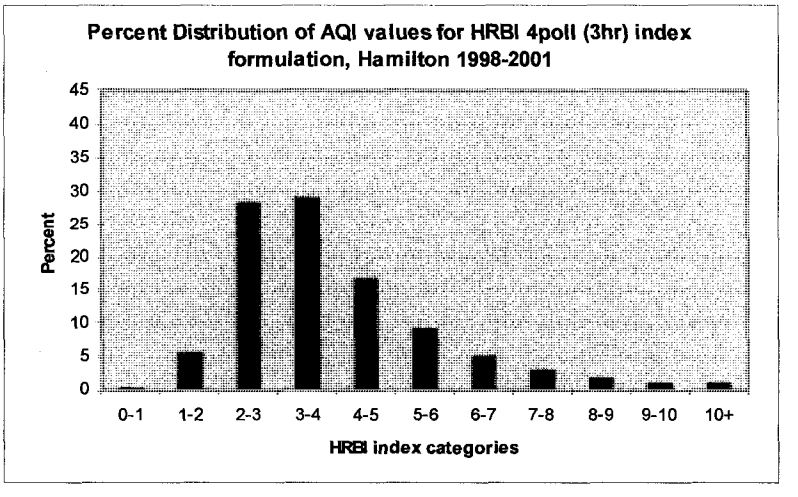


Figure 7e

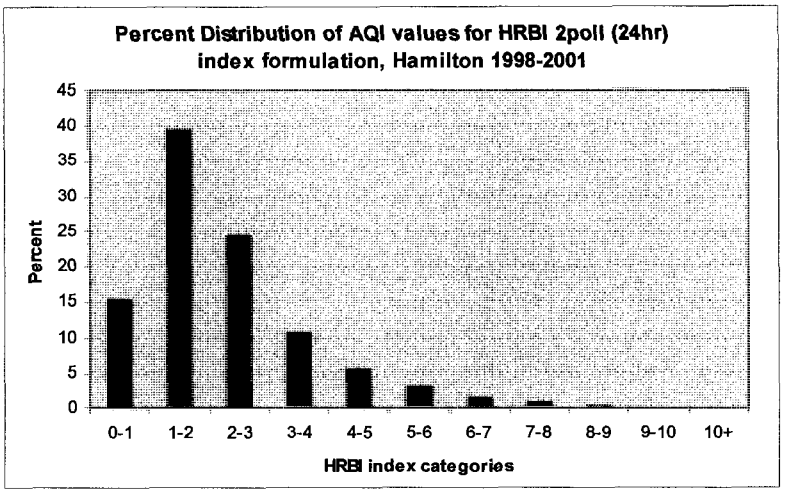


Figure 7f

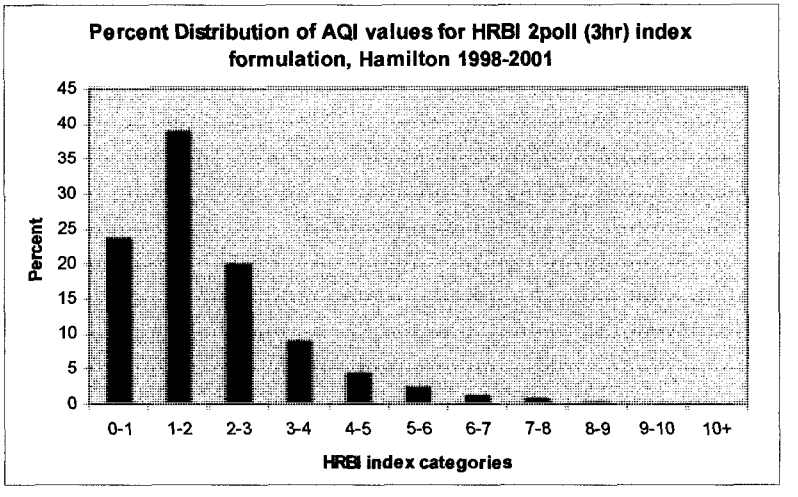


Figure 7g

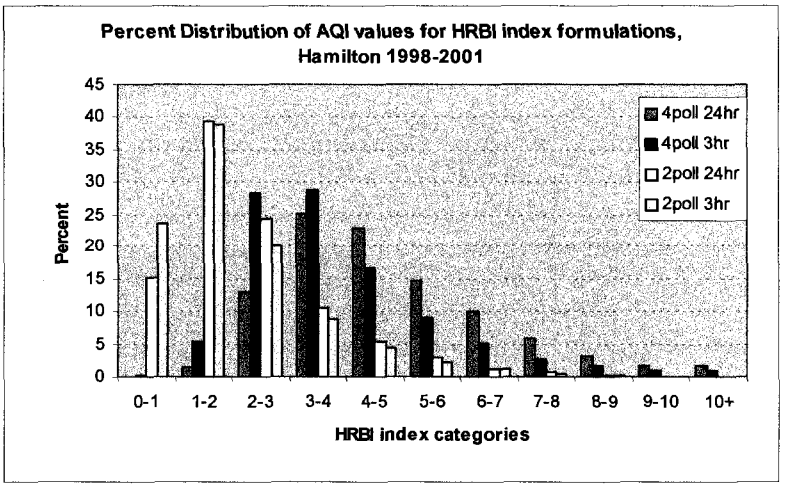


Figure 7h

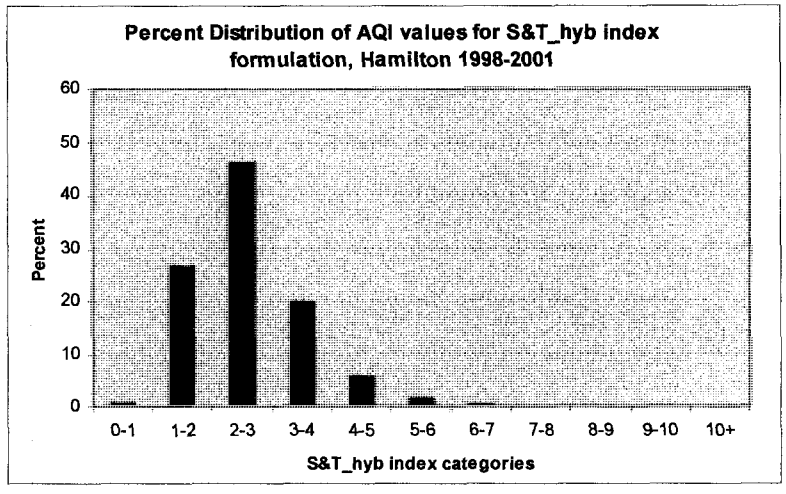
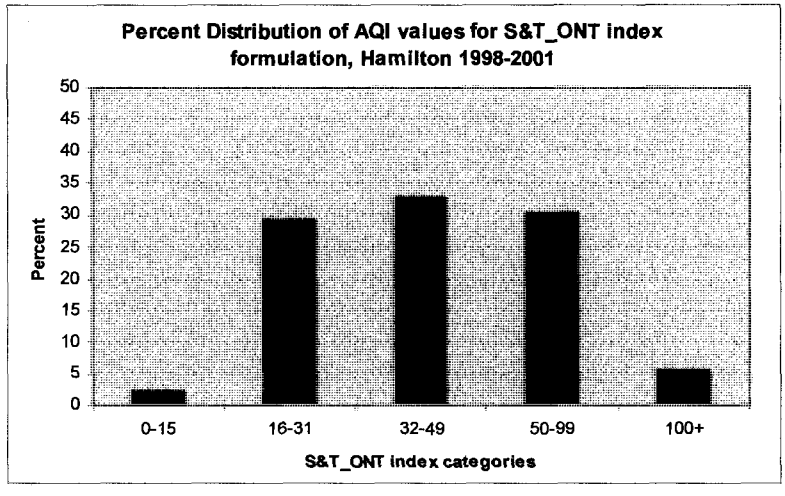


Figure 7i



Toronto

A similar percent distribution of values is observed using the Toronto dataset (see Figures 8a to 8i). Differences are noted in the percent distribution of AQI values using the AQIONT and AQIEPA, where there are an even greater percentage of values at low AQI levels than with the Hamilton dataset. The HRBI 4 pollutant formulations are also less skewed to the right for the Toronto dataset, resulting in an increased percentage of values at higher AQI levels.

Figure 8a

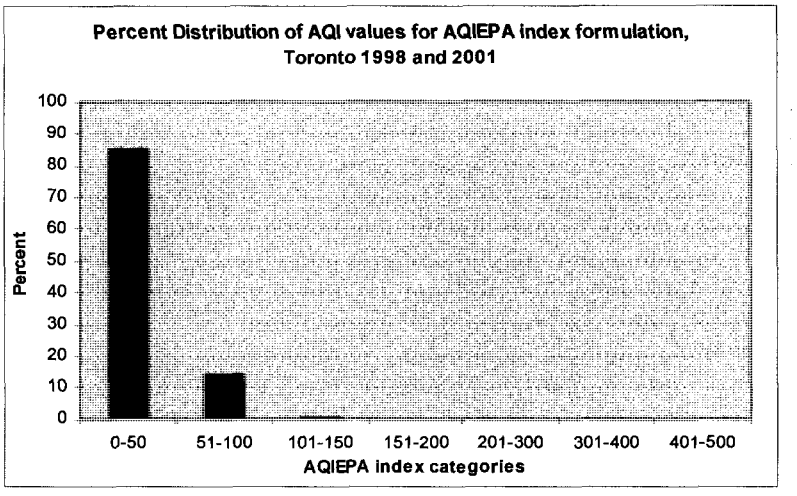


Figure 8b

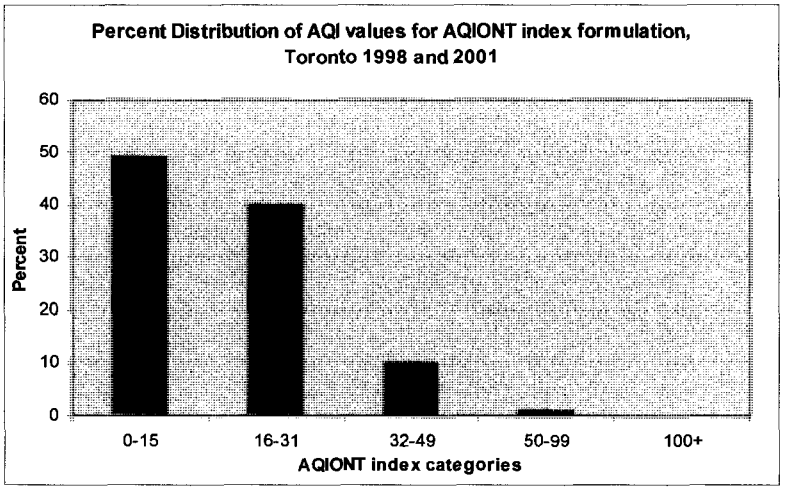


Figure 8c

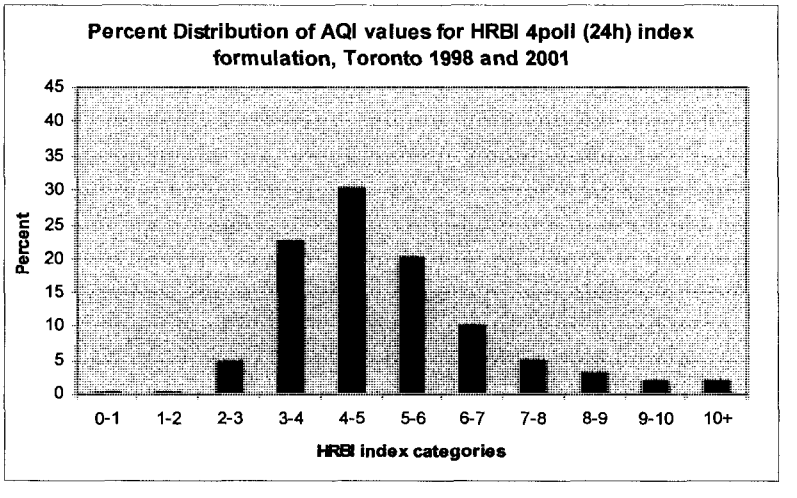


Figure 8d

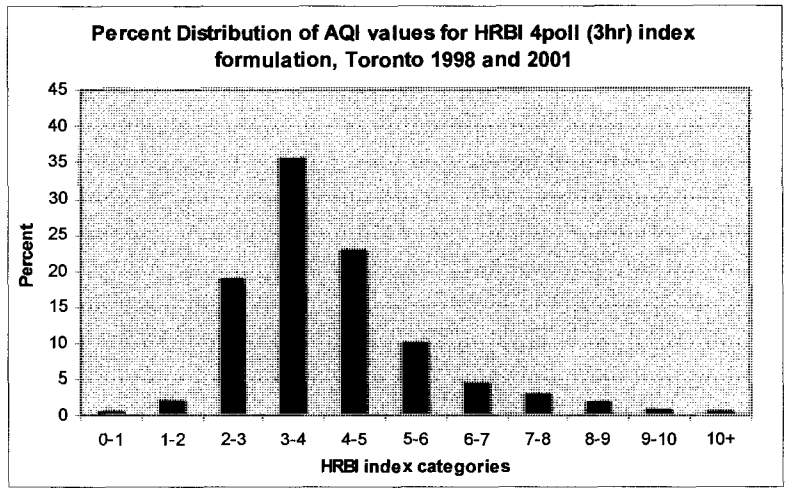


Figure 8e

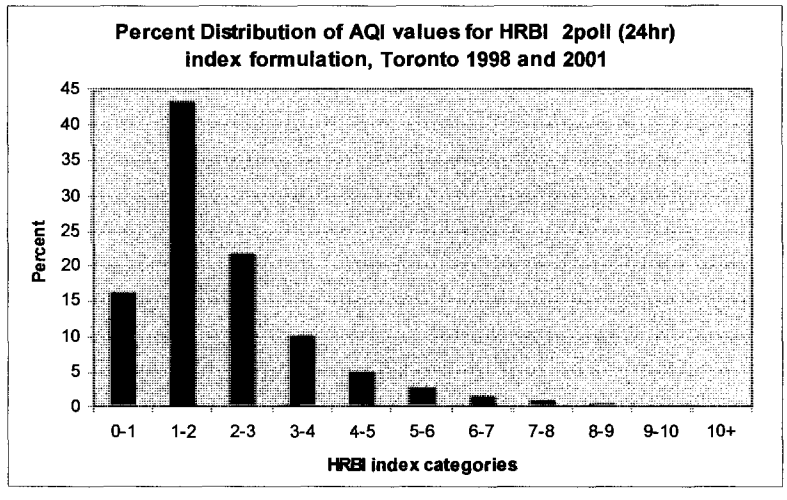


Figure 8f

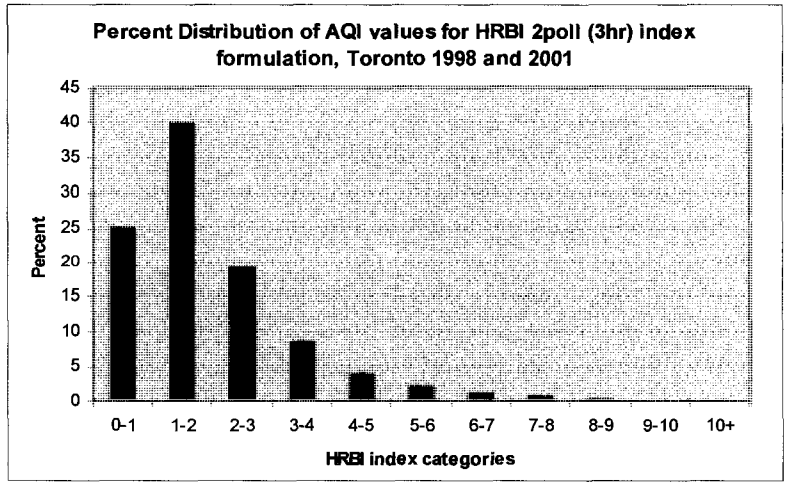


Figure 8g

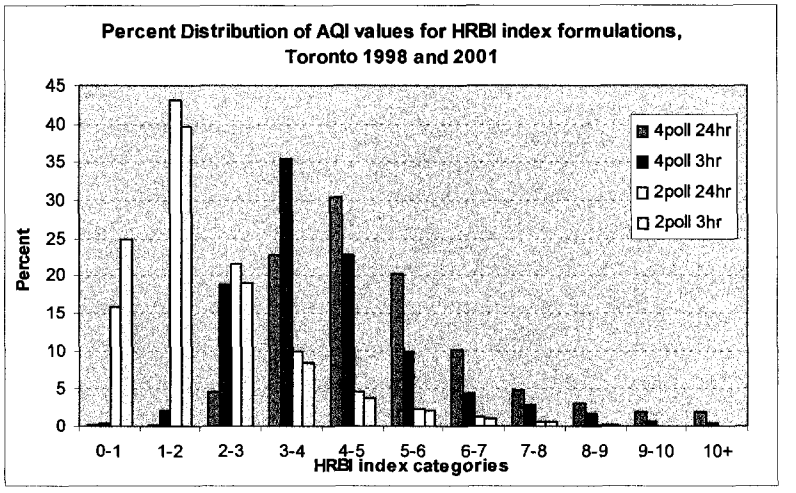


Figure 8h

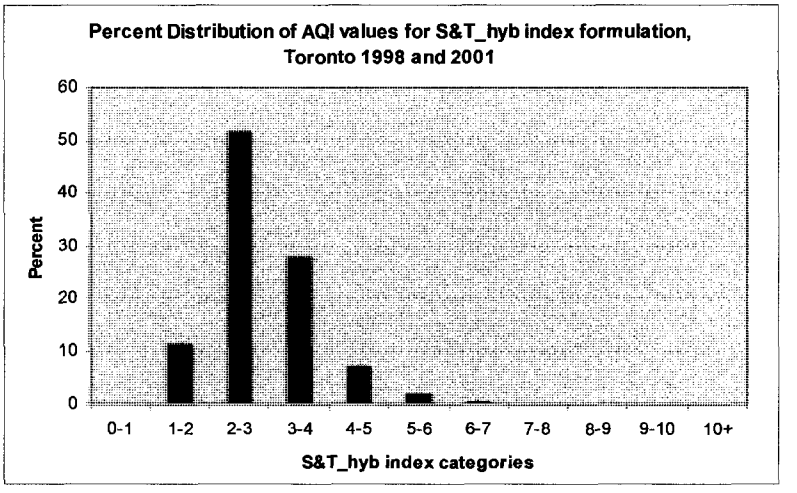
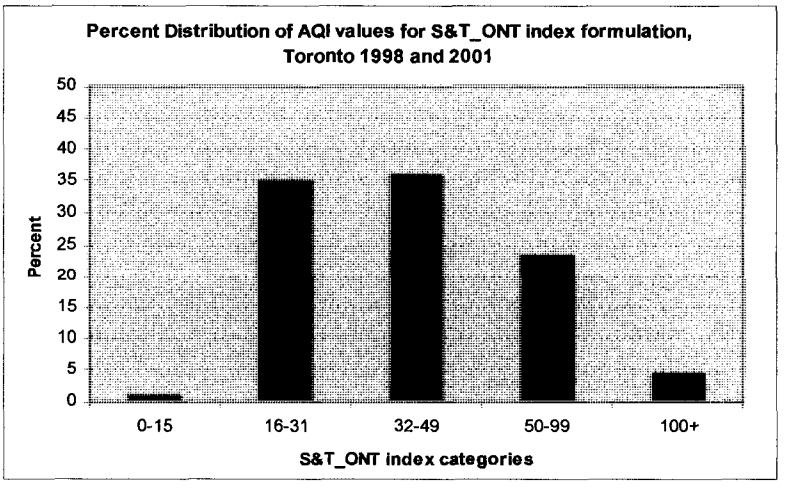


Figure 8i



Ottawa

Overall, similar percent distributions are also observed with the Ottawa dataset (see Figures 9a to 9i). In contrast, the percentage of moderate or poor level AQI values for the AQIONT and AQIEPA formulations is about half that observed for the Hamilton and Toronto datasets. As for the HRBI formulations, the percent distributions are most similar to those observed using the Toronto dataset, except that the distribution of values are concentrated at the lower spectrum of the scale with notably fewer values at the higher categories.

Figure 9a

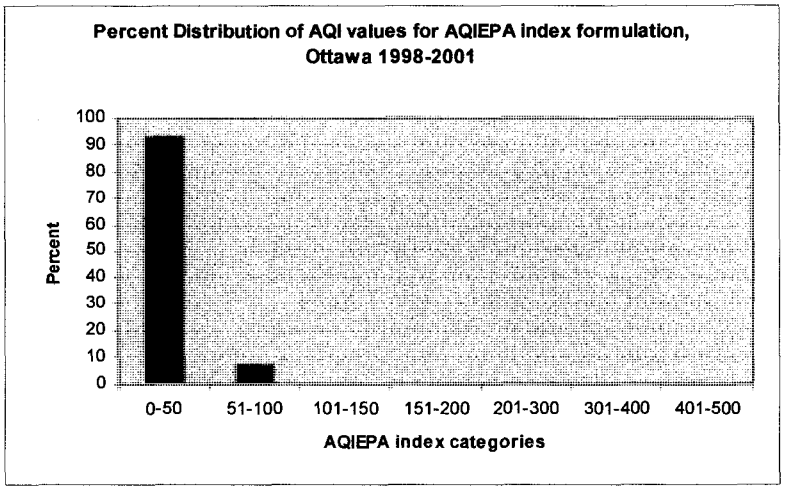


Figure 9b

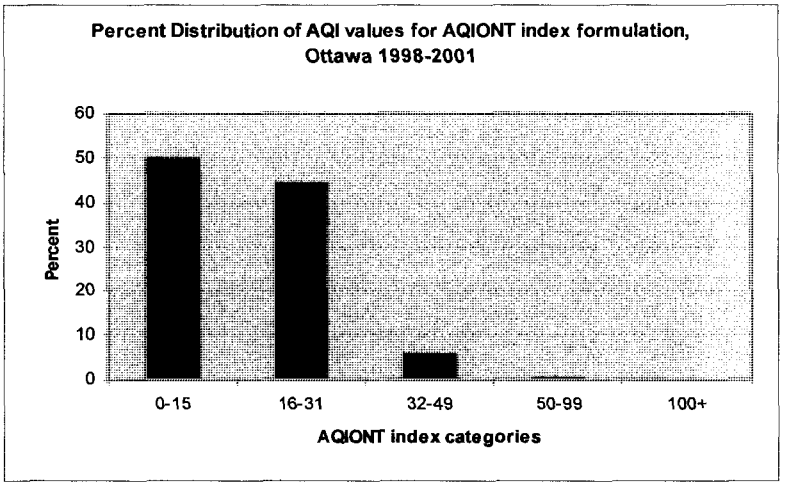


Figure 9c

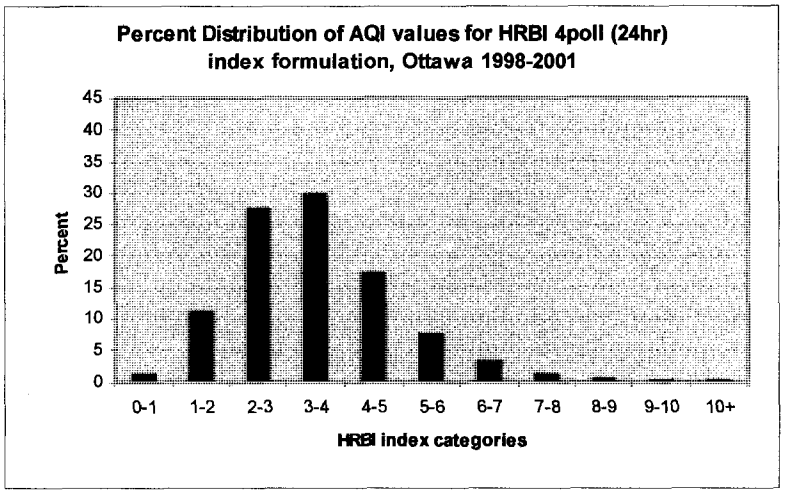


Figure 9d

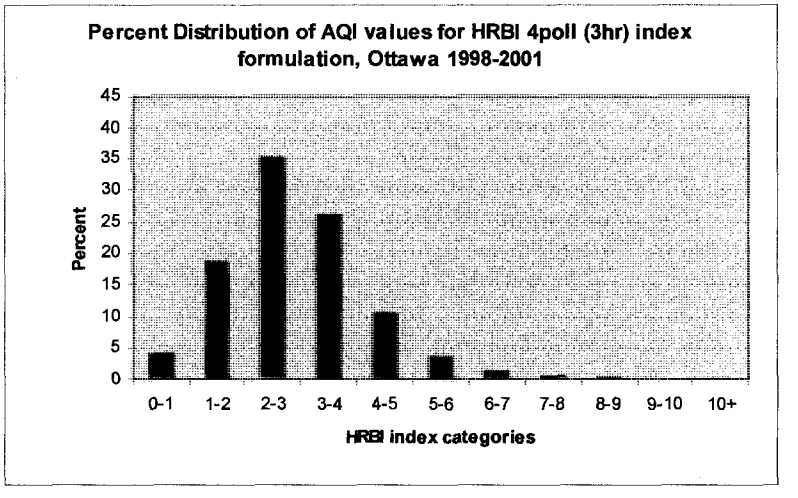


Figure 9e

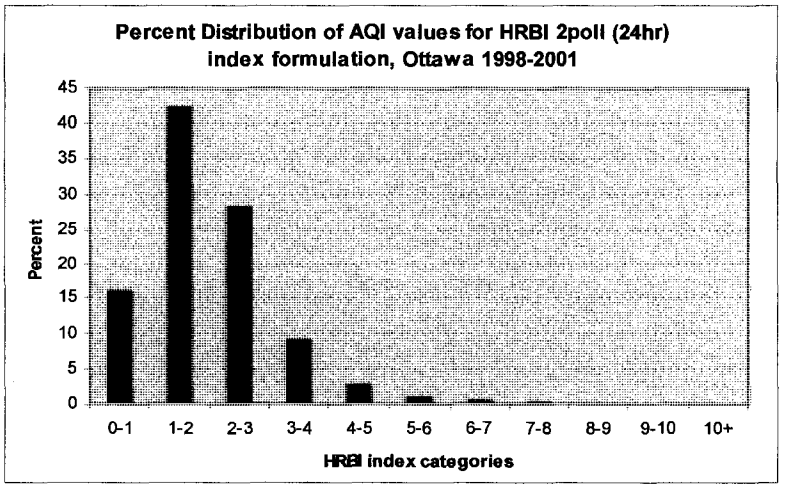


Figure 9f

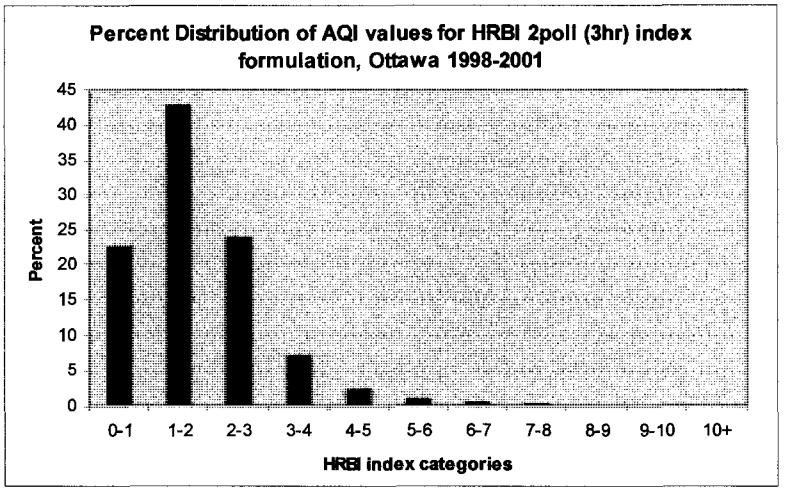


Figure 9g

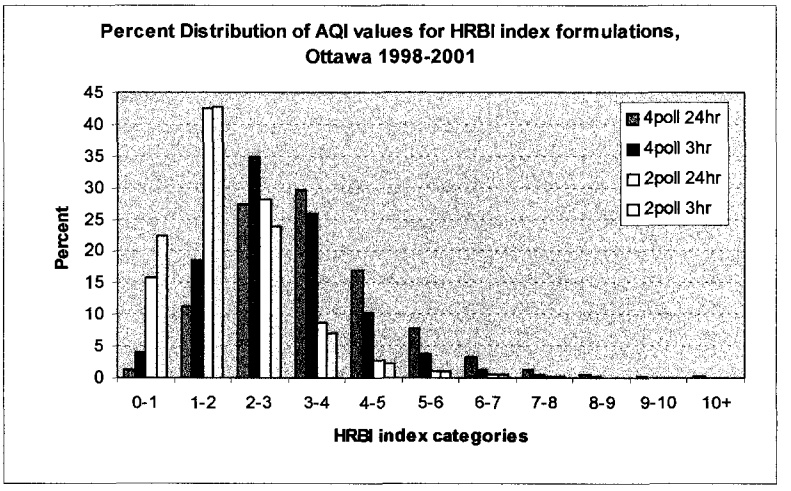


Figure 9h

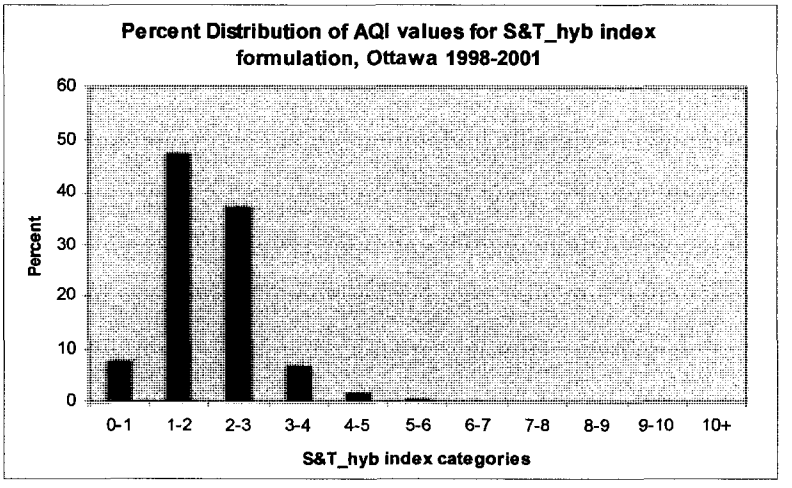
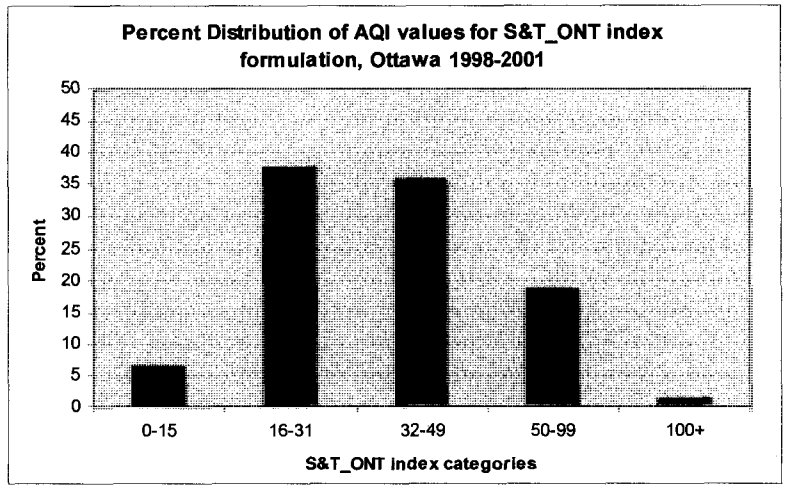


Figure 9i



Windsor

Finally, the percent distribution of AQI values using the Windsor dataset are also similar to those observed for the other Ontario sites (see Figures 10a to 10i). The results are most similar to those found with the Hamilton dataset.

Figure 10a

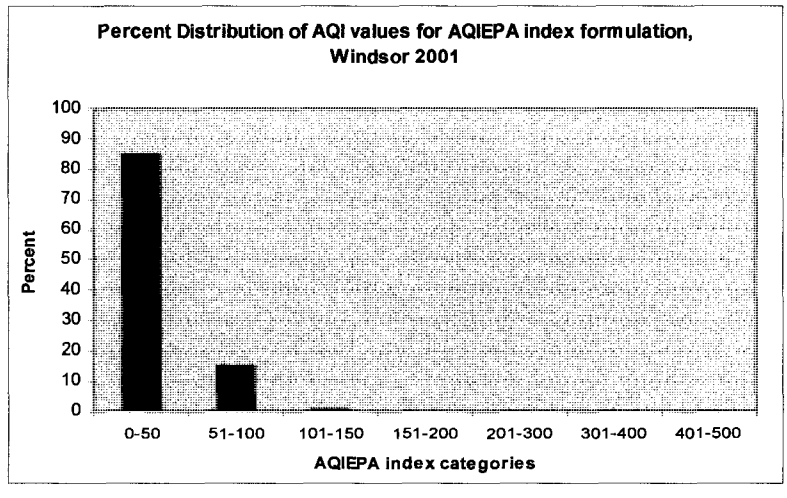


Figure 10b

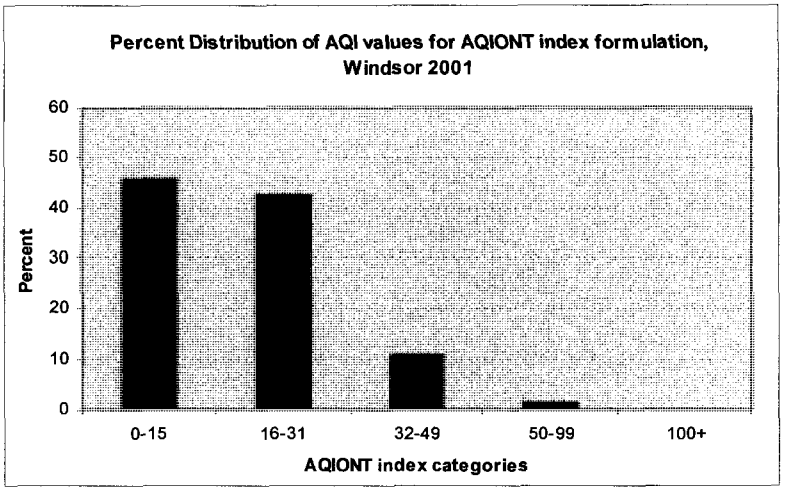


Figure 10c

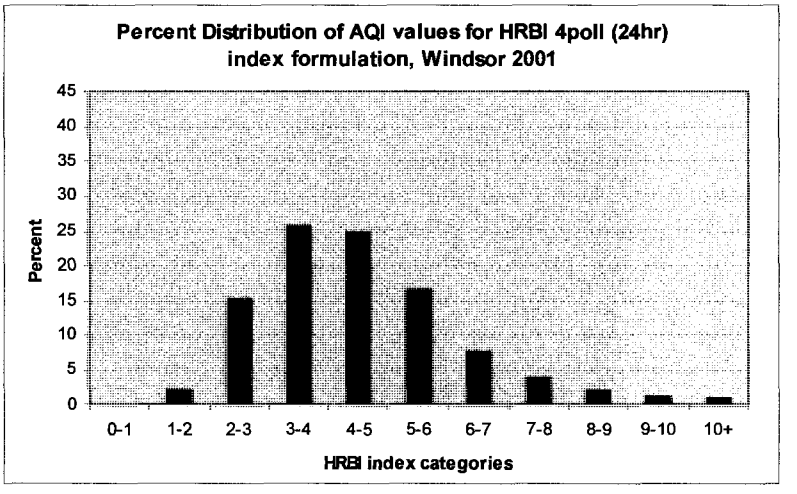


Figure 10d

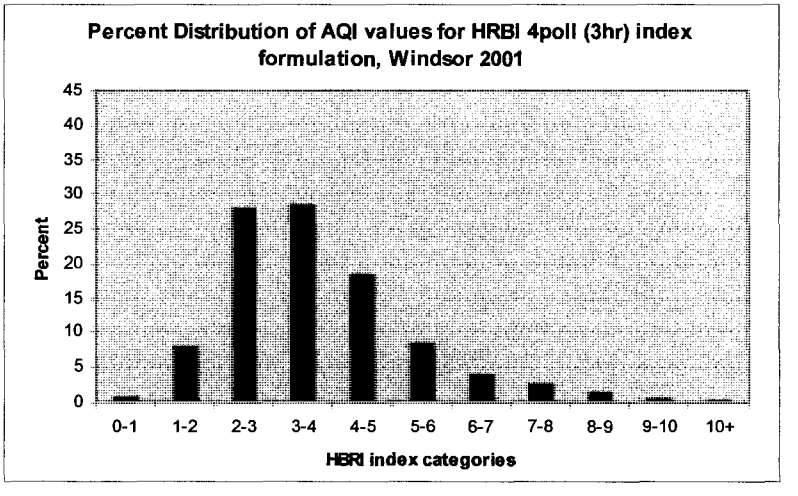


Figure 10e

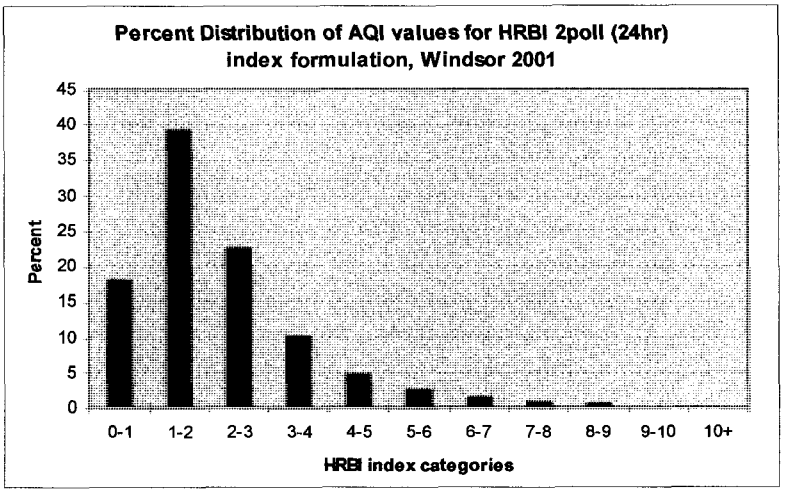


Figure 10f

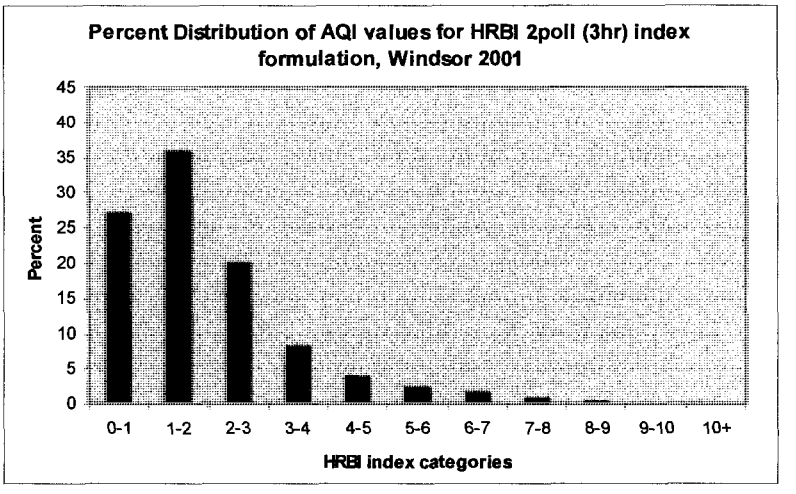


Figure 10 g

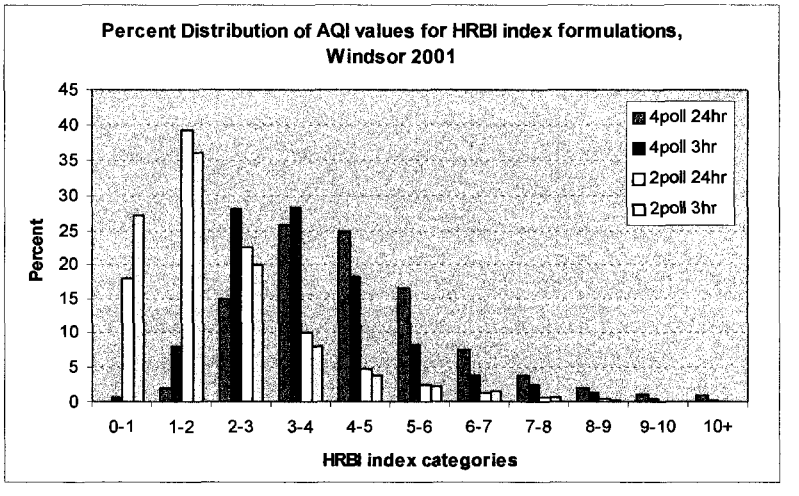


Figure 10h

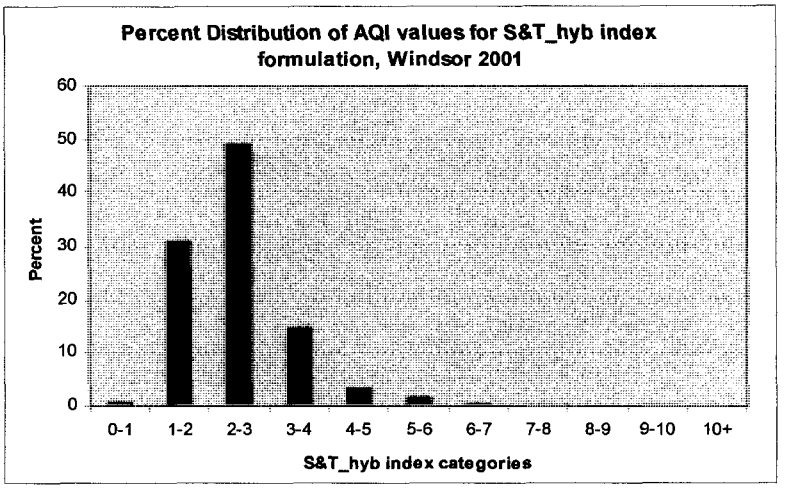
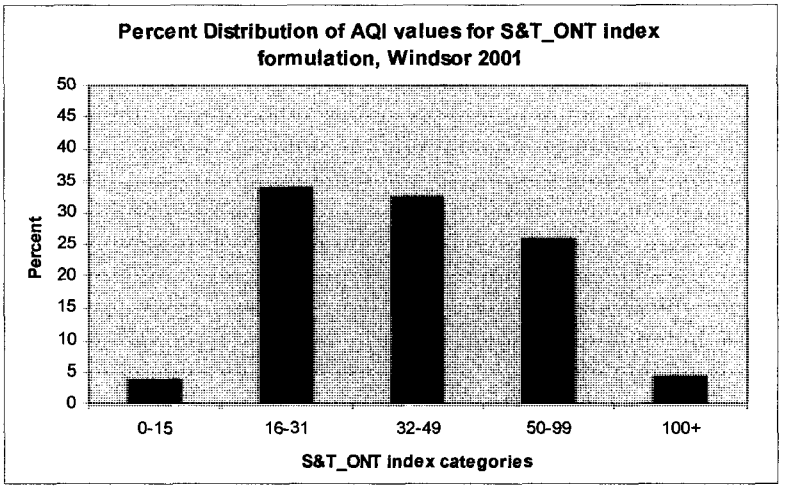


Figure 10i



Overall, it appears that Toronto has the largest percentage of values classified to higher AQI values when using the HRBI formulations and the S&T_Hyb formulation. However, Hamilton, Toronto and Windsor have the largest percentage of high AQI values when using the AQIONT formulation. Hamilton also has the largest percentage of higher AQI values for the AQIEPA and S&T_ONT formulations. This appears to be in overall agreement with the results presented for the descriptive properties of the formulations.

Percentage of AQI values categorized as 'high/poor' for the different AQI formulations

The following figures show the percent distribution of 'high/poor' air quality values for each site with each of the AQI formulations. As previously described in section 6.3.4 *Description of Analysis*, 'high/poor' air quality designations were developed for those AQI formulations currently not used in practice. For the HRBI models, the 85th percentiles of the initial hybrid distribution models were used for this assignment based on additional work completed by Stieb et al. For a qualitative assessment of the S&T models, 'poor' air quality designations from the HRBI 4p 24hr and AQIONT formulations were used. Thus, the results of the S&T models are to be interpreted qualitatively in comparison to the AQI formulation underlying their 'high/poor' air quality designation.

Figure 11 a

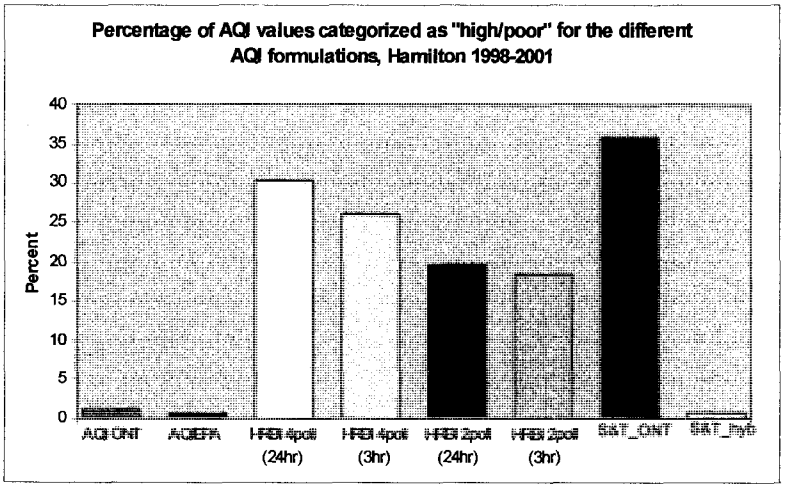


Figure 11b

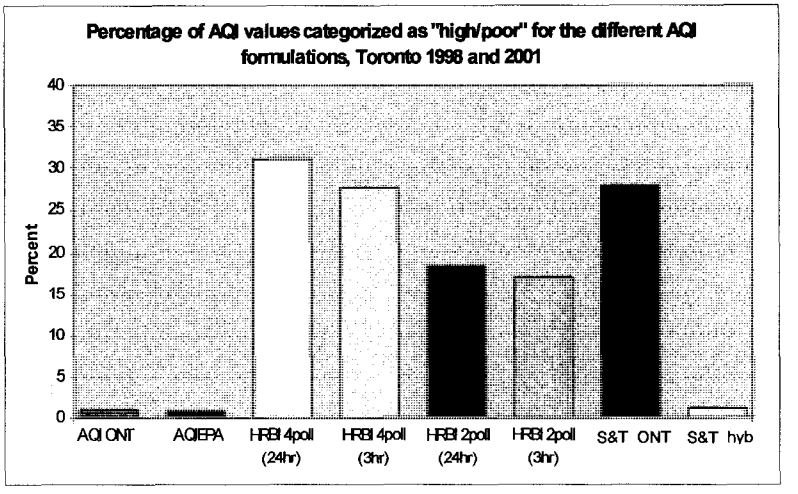


Figure 11c

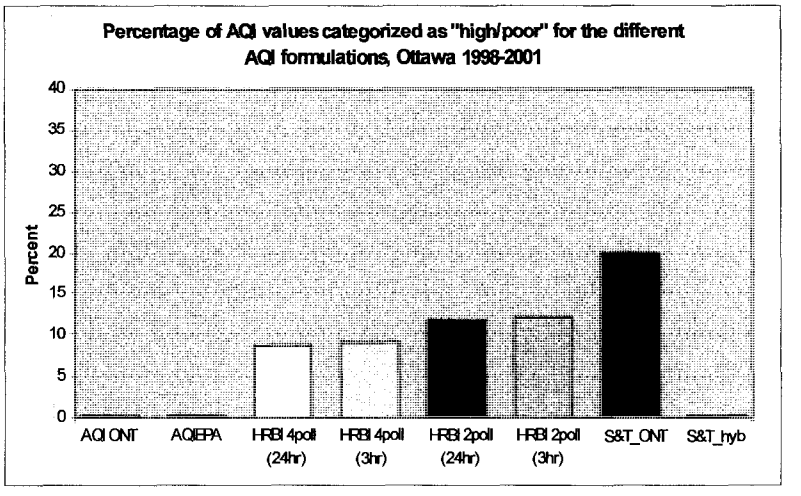


Figure 11d

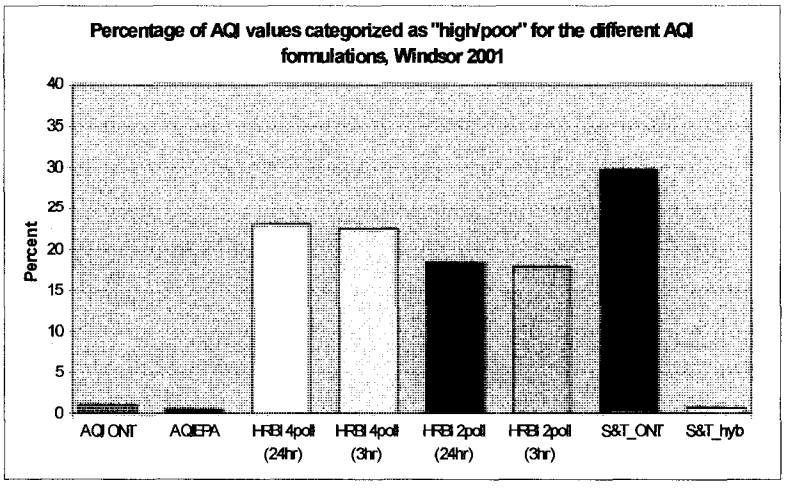


Table 31 also presents a summary of the percent of AQI values categorized as 'high/poor' AQI values for the selected Ontario sites. Additionally, a ranking is provided of the different formulations with the number one rank representing the formulation resulting in the highest percentage of 'high/poor' AQI values. In the comparison of city sites, Toronto is associated with the highest percentage of 'high/poor' air quality hours, followed by Hamilton, Windsor and Ottawa. This is in general accordance with historical information from the OMOE on Ontario air quality conditions. In the comparison of AQI formulations, the HRBI formulations and the S&T_ONT formulation are associated with the highest percentage of 'high/poor' AQI values. In particular, the HRBI 4p 24hr formulation is associated with a high percentage of 'high/poor' values for the Hamilton, Toronto and Windsor sites. The S&T_ONT formulation classified an even higher percentage of values as 'high/poor', except for the Toronto site where the HRBI 4p 24hr was assigned the number 1 rank. The HRBI 4p 3hr is also associated with a high percentage of poor air quality hours for Hamilton, Toronto and Windsor. In contrast, the HRBI 2p formulations for the Ottawa site ranked higher than the HRBI 4p formulations. This suggests that NO_2 and SO_2 have a reduced influence on poor air quality conditions in Ottawa. The AQIEPA was ranked the lowest for all cities, with the least percentage of poor air quality hours followed by the AQIONT and the S&T_Hyb. There is a large gap in terms of the percentages of 'high/poor' index values for the existing formulations, the AQIEPA and AQIONT, and the proposed HRBI formulations. Additionally, the S&T_ONT formulation that is constructed based on existing standards has a vastly greater percentage of poor air quality hours when compared to the AQIONT. This could be due to the differences in the formulations themselves or the $PM_{2.5}$ standard used in the

S&T_ONT formulation. Along these lines, the S&T_Hyb is dissimilar to the HRBI formulations in terms of the percentage of poor air quality hours.

Table 31. Percent of hours considered 'high/poor' air quality and Index Rankings for select Ontario sites

	Def'n of Poor*	Hamilton		Toronto		Ottawa		Windsor	
		Percent	Rank	Percent	Rank	Percent	Rank	Percent	Rank
AQIEPA	>100	0.60	8	0.69	8	0.12	8	0.49	8
AQIONT	>49	1.19	6	0.94	7	0.19	6	1.13	6
HRBI 4p 24hr	>5.47	30.27	2	31.18	1	8.83	5	22.96	2
HRBI 2p 24hr	>3.10	19.56	4	18.20	4	11.67	3	18.42	4
HRBI 4p 3hr	>4.60	26.04	3	27.67	3	9.19	4	22.54	3
HRBI 2p 3hr	>2.93	18.26	5	17.03	5	12.02	2	17.85	5
S&T_Hyb	>5.47	0.76	7	1.09	6	0.16	7	0.77	7
S&T_ONT	>49	35.74	1	27.92	2	19.97	1	29.95	1

* Index value for each formulation representing 'high/poor' air quality

6.4.2 Analyses supporting an analytical comparison of AQIs

1. What are the results of each AQI formulation when inputting moderate-level pollutant concentrations, versus higher-level pollutant concentrations?

The median, 75th and 95th percentile pollutant concentrations from the original NAPS Canada wide dataset were calculated and used in this investigation. The pollutant concentrations are presented in Table 32 and the AQI values obtained by entering these concentrations into each AQI formulation are presented in Table 33. By entering the median pollutant concentrations nearly all of the formulations resulted in either 'low/good' or 'medium/moderate' air quality categorizations. The 75th percentile pollutant concentrations resulted in a moderately 'high/poor' index categorization for the HRBI 4p 24hr formulation, and 'medium/moderate' categorizations for the remainder of the HRBI formulations showing the multiple pollutant contribution; whereas, the AQIEPA and AQIONT formulations maintained their 'good' air quality categorizations.

Using the 95th percentile pollutant concentrations, both the HRBI 4p 24hr and the HRBI 4p 3hr formulations resulted in 'high/poor' categorizations while the other formulations result in only 'medium/moderate' level categorizations. Using the same scale as the AQIONT, the S&T_ONT formulation is the most sensitive in declaring 'higher/poorer' air quality conditions. However, as previously mentioned this scaling may not be an appropriate classification for this formulation and should not be interpreted quantitatively. Overall, very 'high/poor' categorizations are not observed. This is probably due to the pollutant concentrations used for this examination. Considering the large dataset used for the pollutant concentration determinations and that data were averaged across all Canadian regions, the 95th percentile may not be representative of very high pollutant concentrations. Very high concentrations are probably observed at even greater percentiles.

Table 32. Median, 75th percentile and 95th percentile Pollutant Concentrations, NAPS data from 10 Canadian cities, 1998-2000

	Units	Median conc'n	75th pctl conc'n	95th pctl conc'n
SO_2	ppb	3.33	5.60	**11.00**
NO_2	ppb	18.93	25.00	36.14
CO	ppm	0.63	0.98	1.57
O_3	ppb	27.00	35.50	52.00
$PM_{2.5}$	ug/m^3	7.00	11.00	21.00

Table 33. Index Values and Descriptors using Median, 75th percentile and 95th percentile Pollutant Concentrations, NAPS data from 10 Canadian cities, 1998-2000

	Median		75th pctl		95th pctl	
	Index	**Category**	**Index**	**Category**	**Index**	**Category**
AQIEPA	22.73	Good	35.71	good	62.02	moderate
AQIONT	17.81	Good	22.74	good	32.78	moderate
HRBI 4p 24hr	4.47	Medium	6.19	high	9.79	high
HRBI 2p 24hr	2.42	Low	3.34	medium	5.33	medium
HRBI 4p 3hr	3.81	Medium	5.24	medium	8.22	high
HRBI 2p 3hr	2.27	Low	3.11	medium	4.88	medium
S&T_Hyb	2.44	*Low*	2.95	*low*	4.85	*medium*
S&T_ONT	40.30	*moderate*	54.15	*poor*	89.65	*poor*

2. Are 'high/poor' air quality index values being calculated when there are high pollutant concentrations? and

3. What are the pollutant concentrations underlying 'high/poor' air quality index values and outlier values?

From the hourly plots of AQI values for each formulation, those hours with very 'high/poor' AQI values or inconsistently 'high/poor' AQI values were identified for further investigation. Those hours with maximum AQI values were also determined for each formulation to compare the consistency among the formulations in describing 'high/poor' air quality conditions. A comparison of these hours and the resulting formulations for each individual site are presented below. Some of the AQI values that reflected inconsistent categorizations of air quality conditions across the formulations were also further investigated. In particular, the pollutant concentrations underlying these AQI values were explored.

Hamilton

Table 34 summarizes the specific hours (and associated calendar day), and maximum and inconsistent index values for each formulation using the Hamilton dataset.

The hours that generated the maximum AQI values for each formulation were associated with consistently high AQI values across the various formulations. Only hour 13,267 (July 16th, 1999), the maximum hourly AQI value for the HRBI 2p 24hr formulation, resulted in a 'moderate' air quality categorization for the AQIONT formulation. The AQIONT and HRBI 4p 3hr formulations both had the same hourly maximum value. This could be reflective of their common short-term time averaging. Likewise both S&T formulations had the same maximum AQI value and the second highest AQI values. The consistency among formulations in categorizing hours as 'high/poor' is also observed among the second highest index values except at 14,442 hours (September 3, 1999), which is the second highest index value for the HRBI 4p 24hr formulation. This hour is associated with only a moderate air quality categorization for both the AQIEPA and the AQIONT formulations. These formulations also represent the only single pollutant driven approaches, suggesting that the high values observed for the other formulations could be due to their multiple pollutant considerations. Across all hourly maximum values, the HRBI formulations consistently have high AQI values. The S&T_ONT formulation also has consistently high AQI values. Since this formulation lacks a defined scale, it is difficult to assess the quantitative description of air quality conditions. From the plot of hourly AQI values for the HRBI 4p 3hr formulation (Figure 3d) there are distinct high values around the end of November 2001 that do not appear to have consistent high values across all of the other formulation plots. In fact, only the HRBI 4p formulations are associated with high AQI values. Thus, this hour was chosen for further investigation. The exact hour that was chosen to reflect this inconsistency was 33, 949 (November 24, 2001).

Upon examination of the pollutant concentrations for hour 14,442 (September 3, 1999), both O_3 and $PM_{2.5}$ have moderately high concentrations. SO_2 and NO_2 concentrations are also at least twice as high as the mean and median concentrations reported in Table 34. Thus the multiple pollutant driven approaches are associated with high values for this hour, whereas the AQIEPA and AQIONT do not reach the 'poor' categorization as they rely solely on the maximum singular pollutant effect. At hour 33,949 (November 24, 2001) there are significantly high short-term SO_2 concentrations, nearly equal to the maximum SO_2 concentrations observed for the Hamilton site (see Table 17). The AQIONT and HRBI 3hr formulations that incorporate short-term time averaging capture this peak in SO_2 concentration. The same is also observed for the $PM_{2.5}$ concentrations, albeit to a lesser degree. The HRBI 4p formulations that incorporate the additive effects of SO_2 in their formulations are the only formulations that result in high AQI values for this hour. Even though the HRBI 4p 24hr formulation is associated with lower overall pollutant concentrations, the combined moderate concentrations still contribute to an overall high AQI value. The AQIONT formulation does not reach the 'poor' categorization even with these relatively higher concentrations for SO_2 and $PM_{2.5}$ as they are below the air quality criteria for Ontario.

Table 34. Comparison of Index Values at each Index Formulation Maximum and Outlier Values, Hamilton, 1998-2001

	Hour (mm/dd/yy)	**AQI EPA**	**AQI ONT**	**HBRI 4p 24hr**	**HRBI 2p 24hr**	**HRBI 4p 3hr**	**HRBI 2p 3hr**	**S&T_ Hyb**	**S&T_ ONT**
Maximum Index Value									
AQIEPA	3251 (05/16/98)	153.03	80.69	14.76	7.47	13.53	6.40	7.28	231.13
AQIONT	3232 (05/15/98)	125.88	99.73	14.25	8.69	17.97	9.46	6.35	182.28
HBRI 4p 24hr	3237 (05/15/98)	139.90	73.64	15.01	8.92	12.67	7.64	6.75	205.65

	Hour (mm/dd/yy)	AQI EPA	AQI ONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
HRBI 2p 24hr	13267 (07/16/99)	123.91	48.23	12.46	10.21	9.45	8.32	6.72	188.43
HRBI 4p 3hr	3232 (05/15/98)	125.88	99.73	14.25	8.69	17.97	9.46	6.35	182.28
HRBI 2p 3hr	30378 (06/28/01)	105.84	67.34	12.79	9.07	15.38	9.80	6.49	145.66
S&T_Hyb	3252 (05/16/98)	152.96	76.24	14.91	7.56	13.27	6.46	7.28	231.13
S&T_ONT	3252 (05/16/98)	152.96	76.24	14.91	7.56	13.27	6.46	7.28	231.13
2nd Highest Index Value									
AQIEPA	30069 (06/15/01)	125.39	52.87	14.12	9.07	10.08	7.73	6.50	181.60
AQIONT	30062 (06/15/01)	121.29	80.69	13.52	7.58	14.43	7.91	6.04	174.86
HBRI 4p 24hr	14442 (09/03/99)	96.95	42.05	14.53	8.47	10.81	7.29	6.82	139.45
HRBI 2p 24hr	3234 (05/15/98)	132.19	92.19	14.89	9.23	16.05	9.46	6.68	198.12
HRBI 4p 3hr	30378 (06/28/01)	105.84	67.34	12.79	9.07	15.38	9.80	6.49	145.66
HRBI 2p 3hr	3233 (05/15/98)	129.81	97.39	14.71	9.08	17.17	9.67	6.58	193.56
S&T_Hyb	3251 (05/15/98)	153.03	80.69	14.76	7.47	13.53	6.40	7.25	231.01
S&T_ONT	3251 (05/15/98)	153.03	80.69	14.76	7.47	13.53	6.40	7.25	231.01
Other "Outlier" Index Value(s)									
	33949 (11/24/01)	71.04	46.42	8.04	2.30	12.94	2.91	4.13	90.16

Table 35. Pollutant concentrations used to determine "Outlier" Index Values, Hamilton, 1998-2001

	SO_2	NO_2	CO	O_3	$PM_{2.5}$
Hour 14442 (09/03/99)					
AQIEPA	13.13	50.92	0.85	75.13	38.75
AQIONT	10	46	0.95	54	36
HBRI 24hr/ S&T_Hyb	13.13	50.92	-	75.13	38.75
HRBI 3hr	16.33	32.33	-	72.67	36
S&T_ONT	10	46	0.95	54	38.75
Hour 33949 (11/24/01)					
AQIEPA	21.83	36.75	0.98	2.13	25.58
AQIONT	92	40	0.54	3	41.67
HBRI 24hr/ S&T_Hyb	21.83	36.75	-	2.13	25.58

	SO_2	NO_2	CO	O_3	$PM_{2.5}$
HRBI 3hr	88.33	36.33	-	4	41.67
S&T_ONT	92	40	0.54	3	25.58

* units are ppm for CO, ppb for other gases, and ug/m3 for PM

Toronto

In the examination of the maximum hourly AQI values for Toronto, nearly all of the different formulations are associated with high AQI values for each formulation's maximum (see Table 36). The only formulation where the index value does not reach a 'high/poor' classification is with the AQIONT formulation for the maximum hourly values for the HRBI 24hr formulations. The results of the 2nd highest index value examination, show greater inconsistency among the different formulations. The only hours for which there are consistently high AQI values across the different formulations are with the hourly maximums for the HRBI 24hr formulations and the HRBI 2p 3hr formulation. Additionally, the HRBI 4p formulations are associated with high values for all hourly maximums. The remainder of the formulations show some discrepancies in the categorization of air quality conditions. The AQIONT and the HRBI 2p 3hr formulation are similar in their categorization of AQI values across the different hours. This is probably because of their similar pollutant averaging-times and because the HRBI 2p 3hr formulation does not include NO_2 and SO_2, while the AQIONT is never driven to a poor categorization by NO_2 or SO_2 (see Table 50). It is also interesting to note the differences between those formulations with dissimilar pollutant concentration averaging times. This can be seen among the AQIONT and the HRBI 2p 3hr formulations in comparison to the AQIEPA 2nd highest index value hour at 13,774 (August 2, 2001).

From the plots of hourly AQI values, the hours around the beginning of May 2001 are associated with high AQI values for both of the HRBI 4p formulations, while the remainder of the formulations do not have similarly high values. In particular, hour 11,538 (May 1, 2001) was found to be high only for the HRBI 4p formulations. Further investigation into this discrepancy was conducted through the examination of the associated pollutant concentrations. Hours 12,619 (June 15, 2001) and 12,589 (June 14, 2001) were also chosen for further investigation to help clarify the reasons for their discordant AQI categorizations (see Table 37).

At hour 12,619 (June 15, 2001) the O_3 and $PM_{2.5}$ concentrations are consistently high across the different formulation averaging times; however, the AQIONT concentrations are somewhat lower. This shows the lasting contribution of higher pollutant concentrations over time. Five hours earlier at 12,614 the AQIONT is categorized as 'high/poor' thus the poor air quality conditions are still captured but for only a shorter duration as compared to the other formulations. Hour 12,589 (June 14, 2001) is associated with the 2nd highest AQI value for the HRBI 4p 3hr formulation and is also associated with a high AQI value for the HRBI 4p24hr formulation. This implies that a shorter averaging-time and the contribution of the 4 key pollutants are important in classifying this hour with a high AQI value. Upon examination of the pollutant concentrations, O_3 and $PM_{2.5}$ concentrations are highest for AQIONT even though the AQIONT does not reach a poor categorization at this hour. The HRBI 4p 3hr formulation includes elevated concentrations for SO_2 and NO_2. This shows that although the 3-hour averaging-time might reduce the effect of hourly concentration peaks, it still results in comparable concentrations to the hourly time averages observed for the

AQIONT. Hour 11,538 (May 1, 2001) shows somewhat elevated concentrations across all pollutants less CO. SO_2, O_3 and $PM_{2.5}$ are highest with the AQIONT time averages although these concentrations are still well reflected in the HRBI 3hr formulations. In addition, NO_2 is at an even greater concentration with the HRBI 3hr formulation because of the durative effect of elevated values in the hours prior. Thus, even though SO_2, O_3, and $PM_{2.5}$ concentrations are highest with the AQIONT averaging times, a poor categorization is not reached. Moreover, even though the AQIEPA, HRBI 24hr and S&T_Hyb formulations have the same averaging times, the AQIEPA also does not reach the poor categorization. This is because the maximum pollutant concentration for a singular pollutant is not high enough to reach a 'poor' air quality designation. However, the HRBI 24hr and S&T_Hyb formulations consider the additive contribution of each pollutant, and so even moderately high pollutant concentrations can result in a 'high/poor' AQI values.

Table 36. Comparison of Index Values at each Index Formulation Maximum and Outlier Values, Toronto, 1998 and 2001

	Hour (mm/dd/yy)	AQI EPA	AQI ONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
Maximum Index Value									
AQIEPA	3115 (05/15/98)	141.62	58.59	10.96	10.26	10.80	10.55	7.13	163.07
AQIONT	3113 (05/15/98)	116.08	89.55	10.00	9.18	11.08	10.78	6.25	199.96
HBRI 4p 24hr	12619 (06/15/01)	116.45	48.12	14.24	10.34	10.39	8.78	7.23	177.94
HRBI 2p 24hr	12619 (06/15/01)	116.45	48.12	14.24	10.34	10.39	8.78	7.23	177.94
HRBI 4p 3hr	12614 (06/15/01)	112.59	63.63	12.66	8.48	12.11	10.06	6.11	181.84
HRBI 2p 3hr	3114 (05/15/98)	126.47	66.51	10.61	9.84	11.41	11.13	6.78	171.75
S&T_Hyb	12619 (06/15/01)	116.45	48.12	14.24	10.34	10.39	8.78	7.23	177.94
S&T_ONT	3113 (05/15/98)	116.08	89.55	10.00	9.18	11.08	10.78	6.25	199.96

	Hour (mm/dd/yy)	AQI EPA	AQI ONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
2nd Highest Index Value									
AQIEPA	13774 (08/02/01)	122.43	40.24	12.43	7.92	6.89	4.51	5.86	172.94
AQIONT	13764 (08/02/01)	106.94	72.16	10.02	5.50	10.81	6.67	4.83	150.75
HBRI 4p 24hr	3112 (05/15/98)	96.60	75.15	14.09	8.06	10.03	9.67	6.85	180.98
HRBI 2p 24hr	3115 (05/15/98)	141.62	58.59	10.96	10.26	10.80	10.55	7.13	163.07
HRBI 4p 3hr	12589 (06/14/01)	77.03	47.97	9.28	5.00	11.46	6.73	4.35	117.89
HRBI 2p 3hr	12615 (06/15/01)	113.00	62.14	13.20	9.13	12.01	10.14	6.47	183.01
S&T_Hyb	12618 (06/15/01)	115.63	55.71	14.18	10.29	10.89	9.26	7.20	182.81
S&T_ONT	12617 (06/15/01)	114.56	58.59	13.96	10.02	11.18	9.53	7.03	183.80
Other "Outlier" Index Value(s)									
	11538 (05/01/01)	69.07	40.50	11.37	5.21	11.00	5.83	5.31	105.23

Table 37. Pollutant concentrations used to determine "Outlier" Index Values, Toronto, 1998 and 2001

	SO_2	NO_2	CO	O_3	$PM_{2.5}$
Hour 12619 (06/15/01)					
AQIEPA	5.79	36.33	1.01	89.75	48.25
AQIONT	3	23	0.98	78	43.67
HBRI 24hr/ S&T_Hyb	5.79	36.33	-	89.75	48.25
HRBI 3hr	3.33	20	-	86.67	43.67
S&T_ONT	3	23	0.98	78	48.25
Hour 12589 (06/14/01)					
AQIEPA	8.5	37.17	1.23	37.88	28.63
AQIONT	9	45	1.37	65	43.67
HBRI 24hr/ S&T_Hyb	8.5	37.17	-	37.88	28.63
HRBI 3hr	16.33	50	-	57.67	43.67
S&T_ONT	9	45	1.37	65	28.63
Hour 11538 (05/01/01)					
AQIEPA	15.96	48.63	1.15	45.88	24.58
AQIONT	26	39	0.94	61	34
HBRI 24hr/ S&T_Hyb	15.96	48.63	-	45.88	24.58
HRBI 3hr	22.67	48.67	-	53.67	34
S&T_ONT	26	39	0.94	61	24.58

* units are ppm for CO, ppb for other gases, and ug/m3 for PM

Ottawa

Upon examination of the Ottawa hourly maximum values, the AQIEPA formulation does not have 'poor' AQI values for three of the maximum hours (see Table 38). Similarly the S&T_Hyb formulation is not associated with high AQI values. Along these lines, the HRBI 2p and AQIONT formulations are not associated with 'high/poor' AQI values at hour 761 (February 11, 1998). Thus, there is possibly a contribution effect of either NO_2 or SO_2 that is not reflected in the HRBI 2p formulations or AQIONT. However, the AQIEPA does reach a 'poor' value. This hour will be further investigated. The majority of the formulations reach their maximums at around mid June 1998. When examining the 2nd highest index value, hour 30,135 (June 19, 2001) is an interesting case in that with the AQIEPA formulation this hour is not associated with an even near 'poor' air quality categorization while the AQIONT and the majority of the other formulations have high AQI values at this hour.

The hourly plot of AQI values for the HRBI 4p 3hr formulation (see Figure 5d) shows that around the beginning of February 1999 there is a high AQI value that does not appear to be a 'high/poor' AQI value in the other formulations. Upon closer examination, hour 9,277 (February 1, 1999) is associated with a 'high' AQI value with the HRBI 4p 24hr formulation but has only very low values for the HRBI 2p formulations and moderate values for the AQIEPA and AQIONT formulations. To further investigate some of these differences, hours 761, 30,135 and 9,277 were chosen for closer review of their underlying pollutant concentrations.

At hour 761(February 11, 1998) there are elevated values for NO_2 and SO_2 that are not represented in the HRBI 2p formulations. This could explain why these

formulations do not assign a 'high' value at this hour. However, the $PM_{2.5}$ concentrations are well above the mean and median concentrations for Ottawa almost nearing the maximum value. On the other hand the O_3 concentrations tend to be low. This high $PM_{2.5}$ concentration contributes to a 'poor' classification for the AQIEPA, which implies that the AQIEPA formulation assigns a greater weighting to $PM_{2.5}$ than the AQIONT or HRBI 2p formulations since the $PM_{2.5}$ concentrations are identical or almost identical among the different formulations. At 30,135 (June 19, 2001) the AQIEPA and S&T_Hyb formulations are associated with moderate AQI values, while the other formulations have high values or in the case of the HRBI 2p 24hr formulation a moderately high AQI value. From the pollutant concentrations it is obvious that O_3 is driving the final AQI value. Since this time the AQIEPA does not reach a 'poor' categorization there is probably a lesser weight assigned to O_3 than with the other formulations. From the hourly plot of AQI values for the AQIEPA formulation (see Figure 5a), it does not appear that the AQIEPA reaches the 'poor' air quality categorization at any of the nearing hours. Conversely, with the AQIONT there are several hours around this time that result in poor classifications. At hour 9,277 (February 1, 1999) a NO_2 concentration peak is reflected in the formulations with shorter averaging times. This coupled with the higher $PM_{2.5}$ concentration, contributes to a 'high' categorization for the HRBI 4p 3hr formulation. The HRBI 4p 24hr formulation although associated with only moderately high concentrations does result in a slightly 'high' AQI value. The HRBI 2p formulations both have very low AQI values because the O_3 concentration is very low and the elevated $PM_{2.5}$ concentration alone does not result in a high value. This highlights some of the differences in using a multiple pollutant driven formulation with short pollutant

averaging times. The HRBI 4p 3hr formulation declares 'high/poor' air quality conditions while the other formulations do not.

Table 38. Comparison of Index Values at each Index Formulation Maximum and Outlier Values, Ottawa, 1998-2001

	Hour (mm/dd/yy)	AQI EPA	AQI ONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
Maximum Index Value									
AQIEPA	4471 (06/16/98)	110.79	51.01	8.99	7.48	6.96	5.39	4.90	154.39
AQIONT	4457 (06/15/98)	94.41	60.03	9.27	7.81	9.60	8.59	5.22	160.82
HBRI 4p 24hr	761 (02/11/98)	107.10	45.14	11.33	4.80	8.51	3.53	5.57	146.63
HRBI 2p 24hr	4463 (06/15/98)	105.05	54.35	10.82	9.16	9.79	8.31	6.13	157.75
HRBI 4p 3hr	4459 (06/15/98)	99.08	57.32	10.06	8.51	10.84	9.48	5.70	156.52
HRBI 2p 3hr	4459 (06/15/98)	99.08	57.32	10.06	8.51	10.84	9.48	5.70	156.52
S&T_Hyb	4463 (06/15/98)	105.05	54.35	10.82	9.16	9.79	8.31	6.13	157.75
S&T_ONT	4457 (06/15/98)	94.41	60.03	9.27	7.81	9.60	8.59	5.22	160.82
2nd Highest Index Value									
AQIEPA	761 (02/11/98)	107.10	45.14	11.33	4.80	8.51	3.53	5.57	146.63
AQIONT	30135 (06/19/01)	78.40	57.87	8.13	6.49	9.17	8.28	5.14	121.46
HBRI 4p 24hr	4463 (06/15/98)	105.05	54.35	10.82	9.16	9.79	8.31	6.13	157.75
HRBI 2p 24hr	30930 (07/22/01)	98.07	47.53	9.83	8.45	8.49	7.50	5.91	135.55
HRBI 4p 3hr	31530 (08/16/01)	83.24	50.67	9.15	6.90	10.32	8.35	5.41	114.27
HRBI 2p 3hr	13245 (07/16/99)	87.93	51.39	9.28	7.72	9.98	8.78	5.25	143.84
S&T_Hyb	4464 (06/16/98)	105.95	55.09	10.81	9.15	9.53	8.28	6.11	160.11
S&T_ONT	4474 (06/16/98)	110.38	40.76	8.47	6.97	6.56	5.52	4.61	160.62
Other "Outlier" Index Value(s)									
	9277 (02/01/99)	63.33	46.42	7.00	1.99	9.73	2.96	4.39	81.25

Table 39. Pollutant concentrations used to determine "Outlier" Index Values, Ottawa, 1998-2001

	SO_2	NO_2	CO	O_3	$PM_{2.5}$
Hour 761 (02/11/98)					
AQIEPA	17.92	50.21	2.63	16.25	43.50
AQIONT	13	68	3	4	40.00
HBRI 24hr/ S&T_Hyb	17.92	50.21	-	16.25	43.50
HRBI 3hr	13.67	57.00	-	14.67	40.00
S&T_ONT	13	68	3	4	43.50
Hour 30135 (06/19/01)					
AQIEPA	4.27	13.21	0.62	74.63	15.96
AQIONT	-	13	0.65	92	33.00
HBRI 24hr/ S&T_Hyb	4.27	13.21	-	74.63	15.96
HRBI 3hr	-	13.33	-	89.33	33.00
S&T_ONT	-	13	0.65	92	15.96
Hour 9277 (02/01/99)					
AQIEPA	6.75	47.21	2.75	2.50	21.67
AQIONT	9	93.00	3	5	41.67
HBRI 24hr/ S&T_Hyb	6.75	47.21	-	2.50	21.67
HRBI 3hr	10.33	86.67	-	4.67	41.67
S&T_ONT	9	93.00	3	5	21.67

* units are ppm for CO, ppb for other gases, and ug/m3 for PM

Windsor

From the plots of hourly AQI values in Figures 6a to 6h, Windsor appears to have many hours where there are inconsistent air quality categorizations across the formulations. Yet, for the hourly maximum values associated with each formulation, the great majority of the formulations categorize the maximum hour for each formulation as 'high/poor'. Upon examination of the 2nd highest index value, hour 4,290 (June 28, 2001) does not result in 'high/poor' classifications for either the AQIEPA or AQIONT. Further, the HRBI 2p 3hr formulation only has a slightly high AQI value.

Some of the outlier values that appear inconsistent across formulations are hour 5,443 (August 15, 2001) where the AQI values for the AQIEPA and AQIONT are in the

'good' air quality category and the HRBI 2p formulations are moderate but the HRBI 4p formulations have 'high' AQI values. Hour 6,230 (September 17, 2001) is also very high for the HRBI 4p 3hr formulation but is not high or even near high for any other formulation. At hour 5,684 (August 25, 2001) the AQIEPA only has a lower moderate AQI value while the remainder of the formulations classify this hour as 'high/poor'.

From the associated pollutant concentrations in Table 41 for hour 4,290 (June 28, 2001) the O_3 concentrations are high across the different formulation averaging times although they are highest for the formulations using a 24hr time average. Still the AQIEPA does not reach a poor categorization but is nearer to poor than the AQIONT. At hour 5,684 (August 25, 2001) high $PM_{2.5}$ concentrations are observed for the formulations relying on shorter averaging times. This results in a poor categorization for the AQIONT and the HRBI 3 hour formulations. Still, the HRBI 24hr formulations that incorporate the added effects of O_3 also result in high AQI values. At hour 5,443 (August 15, 2001) the particular contribution of NO_2 is noted thus explaining the differences between the HRBI 4p and 2p formulations. Finally, at hour 6,230 (September 17, 2001) a substantial difference in SO_2 concentrations is observed between the formulations using short-term time averages and those using the longer-term time averages. Thus the ability of the 24-hour time-averaging formulations is compromised in capturing short-term peak concentrations. The remainder of the pollutants have relatively lower concentrations. For this hour it was only the HRBI 4p 3hr formulation that reached a 'high/poor' categorization, thus showing the importance of SO_2 in driving a high AQI categorization. This same high categorization is not observed for the AQIONT even with the same high

SO_2 concentration reflecting either a lower weight assigned to this pollutant or the lack of a multiple pollutant driven effect.

Table 40. Comparison of Index Values at each Index Formulation Maximum and Outlier Values, Windsor, 2001

	Hour (mm/dd/yy)	AQI EPA	AQI ONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
Maximum Index Value									
AQIEPA	4556 (07/09/01)	121.95	48.12	10.16	6.39	8.12	6.29	6.58	97.67
AQIONT	4795 (07/19/01)	101.93	73.27	10.12	8.72	12.26	11.27	6.27	162.10
HBRI 4p 24hr	4315 (06/29/01)	116.80	47.53	12.82	9.19	10.06	8.12	6.71	140.76
HRBI 2p 24hr	4315 (06/29/01)	116.80	47.53	12.82	9.19	10.06	8.12	6.71	140.76
HRBI 4p 3hr	4795 (07/19/01)	101.93	73.27	10.12	8.72	12.26	11.27	6.27	162.10
HRBI 2p 3hr	4795 (07/19/01)	101.93	73.27	10.12	8.72	12.26	11.27	6.27	162.10
S&T_Hyb	4315 (06/29/01)	116.80	47.53	12.82	9.19	10.06	8.12	6.71	140.76
S&T_ONT	4817 (07/20/01)	114.07	53.55	10.33	8.74	9.73	8.44	5.72	178.85
2nd Highest Index Value									
AQIEPA	4314 (06/29/01)	117.44	52.83	12.80	9.11	10.66	8.55	6.71	143.88
AQIONT	4310 (06/29/01)	80.63	72.27	10.84	7.20	10.32	8.45	5.34	162.37
HBRI 4p 24hr	4290 (06/28/01)	92.59	40.45	12.05	8.05	8.36	6.39	6.10	120.03
HRBI 2p 24hr	4796 (07/19/01)	108.41	71.05	10.39	8.99	11.85	10.88	6.27	147.52
HRBI 4p 3hr	4312 (06/29/01)	110.99	60.03	12.55	8.83	12.18	10.14	6.54	149.77
HRBI 2p 3hr	4312 (06/29/01)	110.99	60.03	12.55	8.83	12.18	10.14	6.54	149.77
S&T_Hyb	4314 (06/29/01)	117.44	52.83	12.80	9.11	10.66	8.55	6.71	143.88
S&T_ONT	4816 (07/20/01)	115.63	53.24	10.10	8.54	9.34	8.25	5.58	175.67
Other "Outlier" Index Values									
	5684 (08/25/01)	69.32	56.58	8.23	6.79	8.93	7.97	4.88	104.78
	5443 (08/15/01)	44.82	30.57	10.46	4.89	7.30	4.48	5.29	68.84
	6230 (09/17/01)	55.38	24.50	4.92	3.20	10.74	3.42	2.53	69.70

Table 41. Pollutant concentrations used to determine "Outlier" Index Values, Windsor, 2001

	SO_2	NO_2	CO	O_3	$PM_{2.5}$
Hour 4290 (06/28/01)					
AQIEPA	9.96	32.29	0.14	80.13	29.75
AQIONT	16	20	0.29	65	20.33
HBRI 24hr/ S&T_Hyb	9.96	32.29	-	80.13	29.75
HRBI 3hr	12.33	14.33	-	74.00	20.33
S&T_ONT	16	20	0.29	65	29.75
Hour 5684 (08/25/01)					
AQIEPA	3.96	11.29	0.08	68.38	24.71
AQIONT	4	10	0.18	61	52.00
HBRI 24hr/ S&T_Hyb	3.96	11.29	-	68.38	24.71
HRBI 3hr	4.67	8.67	-	67.67	52.00
S&T_ONT	4	10	0.18	61	24.71
Hour 5443 (08/15/01)					
AQIEPA	13.58	45.08	0.11	57.38	11.42
AQIONT	5	32	0.19	49	12.00
HBRI 24hr/ S&T_Hyb	13.58	45.08	-	57.38	11.42
HRBI 3hr	12.00	27.33	-	54.33	12.00
S&T_ONT	5	32	0.19	49	11.42
Hour 6230 (09/17/01)					
AQIEPA	15.50	-	0.60	25.25	17.63
AQIONT	64	27	0.28	32	17.67
HBRI 24hr/ S&T_Hyb	15.50	-	-	25.25	17.63
HRBI 3hr	65.33	26.33	-	34.00	17.67
S&T_ONT	64	27	0.28	32	17.63

* units are ppm for CO, ppb for other gases, and ug/m3 for PM

Through this investigation it was revealed that even the hours associated with the maximum AQI values for some formulations, are not necessarily represented as 'high/poor' across all the different formulations. The formulations based on the maximum operator approach, AQIEPA and AQIONT, displayed the greatest inconsistencies; while the HRBI and S&T_Hyb formulations were generally always consistent in classifying the maximum and 2nd highest AQI values as 'high/poor'. These formulations consider the additive contribution of each pollutant and as such, even

moderately high pollutant concentrations can result in 'high/poor' final AQI values. Yet, even when the same or similar pollutant concentrations were observed as the inputs into the other AQI formulations, the HRBI formulations resulted in high AQI values whereas the same was not consistently observed for the AQIEPA and AQIONT formulations. The HRBI 4p formulations were also driven by the contribution of NO_2 and SO_2 concentrations in declaring some hours as high while the 2p formulations did not. The HRBI 4p 24hr was generally consistent in its categorization of air quality conditions with the HRBI 4p 3hr formulation; although, less sensitivity to peak pollutant concentrations was observed. This resulted in some hours not being classified to the 'high' AQI value range. The HRBI 4p 3hr formulation was sensitive to peak pollutant concentrations and was also able to capture peak concentrations among all 4 pollutants. As such, for some hours it was the lone formulation categorizing air quality conditions as 'high/poor'.

These results have shown that the different AQI formulations are reflective of their conceptual basis in terms of declaring increasingly *worse* classifications of air quality with increasing pollutant concentrations. The results of these investigations also revealed that there are differences in the categorization of air quality conditions by using different AQI formulations. The AQIEPA and AQIONT were less consistent in declaring 'high/poor' air quality conditions when the remainder of the formulations declared conditions as such. This raises the question of whether air quality conditions were in fact 'high/poor' and these formulations failed to classify the air quality conditions as such, or whether the HRBI and S&T formulations were falsely declaring 'high/poor' air quality conditions.

4. What is the percentage contribution of each pollutant to the HRBI AQI formulations?

The HRBI formulations were further investigated to assess the percentage contribution of each pollutant to the final AQI value. Since these formulations incorporate a multiple pollutant driven approach the individual pollutant contributions could be assessed whereas the AQIONT and AQIEPA AQI values consist solely of the maximum operator pollutant. The S&T formulations were left out of this investigation because of the difficulties already stated with quantitative interpretations. The results are summarized for each Ontario site below.

Hamilton

The results in Table 42 show that O_3 and NO_2 are associated with the highest percent contributions for the HRBI 4p 24hr formulation, with slightly higher percent contributions for NO_2. SO_2 makes the least percent contribution, although there are some hours that show SO_2 making over a 40 percent contribution to the final AQI value. For $PM_{2.5}$, even if the overall percent contribution is lower than O_3 and NO_2 there are still some AQI values that have a higher contribution, over 40 percent from $PM_{2.5}$. Those few AQI values that result in percent contributions in the 91-100 range represent those hours where only one pollutant was available for the AQI determination. The results of the HRBI 4p 3hr formulation are similar to the HRBI 4p 24hr formulation with O_3 and NO_2 making the largest contributions to the final AQI values. In contrast, SO_2 has an increased percentage contribution, which is reflective of the shorter averaging time peak influence of this pollutant. It is difficult to assess the pollutant contribution differences in the HRBI 2p formulations. By examining the percent contribution of hours above 50

percent O_3 is associated with the highest percentages, which is in agreement with the 4p formulations that show O_3 with higher percent contributions.

Table 42. Percent of hours by the Pollutant Percentage Contribution, HRBI Formulations, Hamilton, 1998-2001

	Percentage Contribution									
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
HRBI 4p 24hr										
SO_2	41.84	40.25	15.76	2.09	0.05	0.009	0	0	0	0
NO_2	0.84	3.98	14.24	24.83	24.84	19.14	9.09	2.69	0.35	0
O_3	21.13	18.31	20.12	17.85	13.42	7.16	1.39	0.21	0.09	0.31
$PM_{2.5}$	15.77	46.13	28.81	7.92	1.20	0.12	0.01	0.003	0.01	0.02
HRBI 2p 24hr										
O_3	8.21	4.44	5.89	7.85	10.99	15.36	17.65	15.26	9.22	5.11
$PM_{2.5}$	5.11	9.22	15.26	17.65	15.36	10.99	7.85	5.89	4.44	8.21
HRBI 4p 3hr										
SO_2	56.27	27.78	10.68	4.24	0.90	0.10	0.01	0.01	0	0.01
NO_2	2.84	12.11	19.17	18.96	16.43	13.41	10.42	5.37	1.21	0.08
O_3	22.01	12.90	13.13	13.55	12.77	11.78	9.21	3.73	0.74	0.19
$PM_{2.5}$	26.50	40.70	24.57	6.73	1.18	0.10	0.02	0.02	0.01	0.17
HRBI 2p 3hr										
O_3	11.54	3.72	4.40	5.39	7.09	9.93	13.88	16.27	15.37	12.42
$PM_{2.5}$	12.42	15.37	16.27	13.88	9.93	7.09	5.39	4.40	3.72	11.54

Toronto

The results of the Toronto site show that NO_2 makes an even larger percent contribution for the 4p 24hr formulation; however, O_3 is still associated with high percent contributions. SO_2 is associated with very low percent contributions reflecting the less industrial and more traffic related nature of the city. Again, $PM_{2.5}$ is associated with some significantly high percent contributions among AQI values, but overall O_3 and NO_2 have consistently high percentage contributions to the final AQI values. The HRBI 4p 3hr formulation shows an increased contribution of $PM_{2.5}$. NO_2 and O_3 continue to be the highest pollutant contributors but in this formulation O_3 makes an even greater

contribution. As in Hamilton for the HRBI 2p formulations, O_3 is found to have a greater pollutant percentage contribution over $PM_{2.5}$.

Table 43. Percent of hours by the Pollutant Percentage Contribution, HRBI Formulations, Toronto, 1998 and 2001

	Percentage Contribution									
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
HRBI 4p 24hr										
SO_2	62.12	33.97	3.63	0.28	0	0	0	0	0	0
NO_2	0.79	0.47	5.20	16.34	25.15	27.25	19.49	5.14	0.14	0.02
O_3	18.40	20.25	22.29	20.65	13.66	3.80	0.47	0	0	0.47
$PM_{2.5}$	26.59	54.19	15.93	3.03	0.14	0.06	0.05	0	0	0
HRBI 2p 24hr										
O_3	3.11	3.82	5.97	7.08	9.84	13.68	18.97	21.52	12.46	3.54
$PM_{2.5}$	3.54	12.46	21.52	18.97	13.69	9.84	7.08	5.97	3.82	3.11
HRBI 4p 3hr										
SO_2	69.73	25.46	4.06	0.60	0.10	0.02	0.02	0.01	0	0
NO_2	1.28	5.11	13.56	17.30	18.95	19.07	16.02	7.72	0.82	0.16
O_3	19.83	14.86	14.44	14.21	14.90	12.43	7.15	1.97	0.15	0.07
$PM_{2.5}$	39.47	41.94	15.40	2.46	0.19	0.05	0.01	0.06	0	0.42
HRBI 2p 3hr										
O_3	4.06	4.80	5.83	5.77	6.52	9.06	13.43	17.15	19.65	13.72
$PM_{2.5}$	13.72	19.65	17.15	13.43	9.06	6.53	5.77	5.83	4.80	4.06

Ottawa

In the same way, NO_2 and O_3 make up the greatest pollutant percentage contributions for the HRBI 4p 24hr formulation; however, in Ottawa O_3 has a slightly higher percent contribution as compared to NO_2. Additionally, SO_2 and $PM_{2.5}$ have an increased percent contribution. Similar to the Hamilton results, the HRBI 4p 3hr formulation has an increased pollutant contribution from SO_2. Consistent results are also observed for the HRBI 2p formulations.

Table 44. Percent of hours by the Pollutant Percentage Contribution, HRBI Formulations, Ottawa 1998-2001

	Percentage Contribution									
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
HRBI 4p 24hr										
SO_2	51.16	34.23	12.40	1.41	0.56	0.19	0.01	0.03	0.01	0
NO_2	5.69	15.85	26.91	19.92	15.73	10.37	4.06	0.98	0.43	0.06
O_3	9.84	9.39	11.16	15.08	17.93	18.90	11.34	4.67	1.36	0.33
$PM_{2.5}$	31.10	43.75	18.02	4.54	1.09	0.61	0.58	0.18	0.02	0.11
HRBI 2p 24hr										
O_3	3.64	2.11	2.72	1.10	5.58	8.93	14.30	20.15	21.91	16.56
$PM_{2.5}$	16.56	21.91	20.15	14.30	8.94	5.58	4.10	2.72	2.11	3.64
HRBI 4p 3hr										
SO_2	57.89	31.91	8.38	1.02	0.37	0.22	0.14	0.03	0.01	0.02
NO_2	18.59	23.26	17.14	12.80	11.58	8.66	5.40	2.00	0.48	0.10
O_3	12.66	7.72	8.42	8.84	11.13	13.40	15.28	13.22	7.35	1.99
$PM_{2.5}$	44.00	32.38	15.33	4.14	1.10	0.39	0.36	0.23	0.02	2.07
HRBI 2p 3hr										
O_3	5.88	2.61	2.82	3.42	4.26	6.08	9.29	14.15	20.56	30.93
$PM_{2.5}$	30.93	20.56	14.15	9.29	6.08	4.26	3.42	2.82	2.61	5.88

Windsor

Similarly in Windsor, NO_2 and O_3 have the highest percent contributions with NO_2 having the highest percent contributions for the HRBI 4p 24hr formulation and O_3 for the HRBI 4p 3hr formulation. SO_2 has an even greater percentage contribution for Windsor in comparison to Toronto and Hamilton. The contributions of SO_2 are again intensified with the HRBI 4p 3hr formulation. And with the HRBI 2 pollutant formulations O_3 is noted as the highest contributing pollutant.

Table 45. Percent of hours by the Pollutant Percentage Contribution, HRBI Formulations, Windsor 2001

	Percentage Contribution									
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
HRBI 4p 24hr										
SO_2	34.82	38.97	18.92	5.83	1.18	0.26	0.02	0	0	0
NO_2	1.63	5.60	16.40	27.46	25.13	16.15	5.97	1.48	0.18	0
O_3	19.18	14.76	16.13	18.68	16.12	10.67	3.85	0.34	0	0.27

	Percentage Contribution									
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**70-80**	**80-90**	**90-100**
$PM_{2.5}$	28.77	43.70	21.22	5.04	1.12	0.14	0.01	0	0	0
HRBI 2p 24hr										
O_3	4.34	5.94	5.92	5.70	7.89	13.12	15.05	17.61	13.74	10.69
$PM_{2.5}$	10.69	13.74	17.61	15.05	13.12	7.89	5.70	5.92	5.94	4.34
HRBI 4p 3hr										
SO_2	53.50	26.06	11.18	5.59	2.58	0.80	0.25	0.02	0	0.01
NO_2	5.13	14.18	19.80	20.24	15.97	11.89	8.70	3.47	0.61	0.02
O_3	21.15	11.56	11.11	11.00	11.78	12.27	11.53	7.49	1.99	0.12
$PM_{2.5}$	38.74	36.81	18.20	4.39	1.09	0.27	0.07	0.09	0	0.36
HRBI 2p 3hr										
O_3	6.44	6.17	5.07	4.89	5.41	7.87	11.46	14.48	16.63	21.59
$PM_{2.5}$	21.59	16.63	14.48	11.46	7.87	5.41	4.89	5.07	6.17	6.44

In summary, NO_2 and O_3 are the pollutants responsible for the greatest percent contribution to the observed AQI values for the HRBI formulations. Nevertheless, the contributory influence of $PM_{2.5}$ and SO_2 is evident and through the examination of hours with 'high/poor' AQI values their influence will be further noted (see Question 6: *What is the percentage of hours for which each pollutant was the driver during 'high/poor' air quality hours?*).

5. What is the percentage of hours for which each pollutant was the driver?

The percentage of hours that each pollutant was the pollutant 'driver', was examined for the AQIEPA, AQIONT and HRBI Formulations. The pollutant 'driver' is defined as the pollutant contributing the largest proportion to the HRBI formulations and the highest pollutant subindex for the AQIONT and AQIEPA formulations. Again, the S&T formulations were left out of this investigation because of difficulties in quantitative interpretation. In this investigation, all AQI values were included (i.e. even 'low/good' index values) to examine the significance of each pollutant as the 'driver' for the final index values. Whereas, in the subsequent investigation, only those AQI values considered to be 'high/poor' were included.

For the AQIEPA formulation, $PM_{2.5}$ is found to be the dominant driving pollutant, being the maximum operator pollutant for the majority of AQI values. It is less dominant in Ottawa where an increased percentage is found for O_3. In Windsor, there is a slightly increased percentage for SO_2 as the driver pollutant. Across all sites, CO is associated with a small percentage of hours where it is the driving pollutant. NO_2 is never the driver pollutant when using the AQIEPA formulation. With the AQIONT formulation both $PM_{2.5}$ and O_3 have fairly equivalent pollutant percentage driver contributions. With this formulation NO_2 is reported as the driver for a small percentage of hours, while CO is nearly never the driver pollutant and SO_2 is only associated with a small percentage for Windsor. With the HRBI 4p formulations NO_2 has the highest percentages for Hamilton and Toronto making it the main pollutant driver for these two cities. In Ottawa the pollutant driver is O_3, and in Windsor the main driver is NO_2 for the 4p 24hr formulation and both NO_2 and O_3 for the 4p 3hr formulation. $PM_{2.5}$ is only associated with a small percentage of hours for these formulations. Again for Windsor, SO_2 is associated with an increasing percentage and in the case of the HRBI 4p 3hr formulation it surpasses the percentage for $PM_{2.5}$ as being the driver. With the HRBI 2p formulations O_3 is the dominant driver across all Ontario sites. These results represent the pollutant drivers across all hours; and yet the hours that are of greatest interest from a public health perspective are those which are associated with the greatest level of health risk. Thus, the next investigation will focus on those hours classified as 'high/poor' to determine if there are any notable differences in the results.

Table 46. Percent of Hours for which Each Pollutant was the "Driver" Pollutant for Select Ontario Monitoring Sites

	AQI EPA[a]	AQI ONT	HRBI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr
SO_2						
Hamilton	0.02	0	0.55	-	3.18	-
Toronto	0.22	0	0	-	0.09	-
Ottawa	0.38	0	0.17	-	0.28	-
Windsor	3.41	0.05	2.20	-	5.52	-
NO_2						
Hamilton	0	1.15	67.63	-	51.88	-
Toronto	0	2.26	80.40	-	63.16	-
Ottawa	0	0.61	35.81	-	31.23	-
Windsor	0	1.78	80.40	-	45.60	-
CO						
Hamilton	2.39	0	-	-	-	-
Toronto	5.55	0.006	-	-	-	-
Ottawa	5.81	0	-	-	-	-
Windsor	0	0	-	-	-	-
O_3						
Hamilton	14.83	43.04	28.17	61.63	42.70	67.16
Toronto	19.80	50.41	18.68	70.81	36.32	74.18
Ottawa	40.39	66.72	62.30	83.14	67.16	83.42
Windsor	25.91	50.51	18.68	68.69	47.19	70.92
$PM_{2.5}$						
Hamilton	82.82	55.80	3.65	38.37	2.24	32.84
Toronto	74.51	47.32	0.92	29.19	0.42	29.08
Ottawa	53.47	32.67	1.72	16.86	1.33	16.58
Windsor	70.67	47.66	0.92	31.31	1.69	29.08

* Based on hours where there were no pollutants missing

[a] AQIEPA O_3 driver represents O_3 8hr. There were no cases where O_3 1hr was the driver pollutant when no pollutants were missing.

6. What is the percentage of hours for which each pollutant was the driver during 'high/poor' air quality index values?

Those hours that were classified as 'high/poor' for each formulation were further investigated to determine which pollutants were 'driving' this poor categorization. For the AQIEPA formulation, the same overall relationship of dominant pollutant driver mentioned under question 5 is observed for this 'high/poor' hour examination. $PM_{2.5}$ is

the dominant driver pollutant, followed by O_3 for all Ontario sites except Windsor. In Windsor, O_3 is the dominant pollutant driver. None of the other pollutants are ever the driving pollutants for these 'high/poor' AQI values. With the AQIONT formulation each Ontario site differs between $PM_{2.5}$ and O_3 as the being the 'driver' pollutant. In Toronto and Ottawa the percentage of hours is fairly equal between the two pollutants. In Hamilton, $PM_{2.5}$ has a significantly higher percentage while in Windsor the majority of the hours are driven by O_3. Similar to the AQIEPA, none of the other pollutants are ever the driver for these poor hour classifications.

With the HRBI 4 pollutant formulations the same overall findings observed for the driver pollutant during all hours are also observed for these hours categorized as 'high/poor' air quality; although, there are greater city variations and it is harder to make any overall conclusions for the formulations. Yet, NO_2 and O_3 are still associated with high percentages making them dominant drivers across all sites and for both HRBI 4p formulations. $PM_{2.5}$ has consistently higher percentages than SO_2 across all sites for the HRBI 4p 24hr formulation but the results of the HRBI 4p 3hr formulation show notably higher percentages for SO_2 in those Hamilton and Windsor where SO_2 tends to be more of a problem. For the HRBI 2p formulations O_3 is by far the dominant driver pollutant. This finding is the same that was observed for the examination of driver pollutants across all hours, but is even further heightened upon examination of 'high/poor' hours. The results of this investigation do highlight the differences between the single pollutant driven and multiple pollutant driven approaches and the HRBI 4p versus 2p formulations. From the HRBI 4p formulations, the importance of all 4 pollutants is noted and demonstrates that if information was missing for even one of the 4 pollutants a potential

misclassification of air quality conditions could occur. The differences in relative weighting for pollutants among the different formulations are also noted. Notably, $PM_{2.5}$ is a dominant driver for the AQIEPA and AQIONT formulations but not for the HRBI formulations.

Table 47. Percent of Hours for which Each Pollutant was the "Driver" Pollutant during "high/poor' hours for Select Ontario Monitoring Sites

	AQI EPA	AQI ONT	HRBI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr
SO_2						
Hamilton	0	0	1.33	-	10.42	-
Toronto	0	0	0	-	0.21	-
Ottawa	0	0	0	-	0.41	-
Windsor	0	0	0.65	-	9.12	-
NO_2						
Hamilton	0	0	56.79	-	34.68	-
Toronto	0	0	65.44	-	49.17	-
Ottawa	0	0	32.65	-	28.28	-
Windsor	0	0	35.64	-	25.88	-
CO						
Hamilton	0	0	-	-	-	-
Toronto	0	0	-	-	-	-
Ottawa	0	0	-	-	-	-
Windsor	0	0	-	-	-	-
O_3						
Hamilton	8.13	24.09	34.54	75.82	49.61	85.82
Toronto	14.29[a]	43.56	31.87	84.11	49.26	91.96
Ottawa	0	53.73	63.54	93.67	69.07	96.76
Windsor	60.47	68.37	57.32	90.49	62.22	96.12
$PM_{2.5}$						
Hamilton	91.87	75.91	7.34	24.18	5.29	14.18
Toronto	85.71	56.44	2.69	15.89	1.36	8.04
Ottawa	100	46.27	3.81	6.33	2.24	3.24
Windsor	39.53	31.63	6.38	9.51	2.77	3.88

[a] AQIEPA O_3 driver represents O_3 8hr. However for Toronto AQIEPA, one of the poor hours was driven by O_3 1hr.

7. What is the correlation between the different AQI formulations?

Spearman correlations were calculated between the different AQI formulations for each Ontario site. All correlations were found to be significant at $p<0.0001$. The AQIEPA was generally highly correlated with the HRBI 24hr formulations and the S&T_Hyb and S&T_ONT formulations. The higher correlations with the HRBI 24hr and S&T_Hyb formulations are probably due to the similar time-averaging used for these formulations. Similarly, the AQIONT formulation which relies on short-term time averages had higher correlations with the HRBI 3hr formulations. Essentially, all of the AQI formulations correlated at least moderately well with each other. The HRBI formulations with the lowest correlation were the HRBI 2p 24hr with the HRBI 4p 3hr formulation probably reflecting the notable differences in pollutant time averaging and pollutant contributions. Also observed were the higher correlations among the HRBI formulations with the same pollutant makeup rather than the same pollutant averaging times. Thus, in this case the association is stronger between formulations with the same pollutant makeup than the same pollutant averaging times. The HRBI 4p 24hr formulation was strongly correlated with the S&T_Hyb formulation reflecting their common pollutant makeup, multiple pollutant driven approach and pollutant averaging times. The S&T_ONT formulation is also strongly correlated with the AQIEPA and AQIONT formulations. Considering that these formulations differ in their formulation approach, there may be individual pollutants that receive similar relative weighting driving this particular correlation.

Table 48. Spearman Correlation among index formulations, Hamilton, 1998-2001

	AQI EPA	AQIONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
AQIEPA	1.0	.	.	.	.	.	.	.
AQIONT	0.70	1.0	.	.	.	.	.	.
HBRI 4p 24hr	0.84	0.68	1.0	.	.	.	.	.
HRBI 2p 24hr	0.71	0.67	0.74	1.0	.	.	.	.
HRBI 4p 3hr	0.63	0.79	0.77	0.59	1.0	.	.	.
HRBI 2p 3hr	0.55	0.81	0.63	0.86	0.68	1.0	.	.
S&T_Hyb	0.76	0.64	0.94	0.60	0.75	0.53	1.0	.
S&T_ONT	0.93	0.83	0.85	0.81	0.70	0.74	0.76	1.0

* all correlations significant p<0.0001

Table 49. Spearman Correlation among index formulations, Toronto, 1998 and 2001

	AQI EPA	AQIONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
AQIEPA	1.0	.	.	.	.	.	.	.
AQIONT	0.66	1.0	.	.	.	.	.	.
HBRI 4p 24hr	0.82	0.65	1.0	.	.	.	.	.
HRBI 2p 24hr	0.67	0.69	0.74	1.0	.	.	.	.
HRBI 4p 3hr	0.60	0.74	0.74	0.58	1.0	.	.	.
HRBI 2p 3hr	0.54	0.83	0.64	0.87	0.66	1.0	.	.
S&T_Hyb	0.73	0.57	0.92	0.53	0.71	0.47	1.0	.
S&T_ONT	0.88	0.84	0.83	0.80	0.69	0.77	0.72	1.0

* all correlations significant p<0.0001

Table 50. Spearman Correlation among index formulations, Ottawa, 1998-2001

	AQI EPA	AQIONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
AQIEPA	1.0	.	.	.	.	.	.	.
AQIONT	0.67	1.0	.	.	.	.	.	.
HBRI 4p 24hr	0.78	0.61	1.0	.	.	.	.	.
HRBI 2p 24hr	0.72	0.71	0.73	1.0	.	.	.	.
HRBI 4p 3hr	0.62	0.68	0.80	0.61	1.0	.	.	.
HRBI 2p 3hr	0.59	0.83	0.62	0.86	0.69	1.0	.	.
S&T_Hyb	0.77	0.66	0.93	0.76	0.78	0.67	1.0	.
S&T_ONT	0.86	0.87	0.75	0.81	0.66	0.80	0.76	1.0

* all correlations significant p<0.0001

Table 51. Spearman Correlation among index formulations, Windsor, 2001

	AQI EPA	AQIONT	HBRI 4p 24hr	HRBI 2p 24hr	HRBI 4p 3hr	HRBI 2p 3hr	S&T_ Hyb	S&T_ ONT
AQIEPA	1.0	.	.	.	.	.	.	.
AQIONT	0.67	1.0	.	.	.	.	.	.
HBRI 4p 24hr	0.82	0.63	1.0	.	.	.	.	.
HRBI 2p 24hr	0.70	0.70	0.74	1.0	.	.	.	.
HRBI 4p 3hr	0.62	0.71	0.75	0.59	1.0	.	.	.
HRBI 2p 3hr	0.58	0.84	0.63	0.88	0.66	1.0	.	.
S&T_Hyb	0.76	0.62	0.94	0.67	0.75	0.59	1.0	.
S&T_ONT	0.87	0.86	0.80	0.80	0.68	0.80	0.74	1.0

* all correlations significant $p<0.0001$

8. How do AQI values differ between different cities?

Throughout this results section, the variations observed among the different Ontario sites have been discussed. As expected, the AQI values across all formulations for Hamilton, Toronto and Windsor were higher than Ottawa reflecting the overall poorer air quality associated with these sites. Using the AQIEPA index formulation, Hamilton and Toronto had the highest percentage of AQI values categorized as 'high/poor', but with the AQIONT formulation Hamilton and Windsor were the cities with the highest percentage of 'high/poor' AQI values. With the HRBI 4p formulations, Windsor has a notably smaller percentage of 'high/poor' AQI values than Hamilton and Toronto. With the HRBI 2p formulations, the three respective cities generally have equivalent percentages of 'high/poor' AQI values. For the S&T_Hyb formulation, the highest percentage of 'high/poor' AQI values was found using the Toronto data followed by Windsor, Hamilton and Ottawa. With the S&T_ONT formulation, Hamilton has a notably higher percentage of 'high/poor' AQI values in comparison to the other cities.

9. How do AQI values differ between seasons?

Observed seasonal variations in AQI values among the different index formulations were previously discussed under the descriptive analysis investigation of hourly changes associated with each of the AQI formulations. A distinct pattern of peaks and valleys was observed with generally higher AQI values observed during the summer months in comparison to the rest of the year, across all index formulations for those Ontario sites containing multiple year datasets. With the one-year dataset for Windsor, notably higher AQI values were observed in the middle of the plot (see Figures 6a to 6h) reflecting that overall higher AQI values are observed in the summer months. Thus, the different AQI formulations are behaving in accordance with known seasonal variations and displaying responsiveness to the pollutant concentrations known to exist for these sites over the different seasons. The observed variability in AQI values across all formulations also reveals that notable differences exist for the categorization of air quality conditions and that in general the formulations are sensitive to pollutant concentration changes.

10. Is the AQI able to capture shorter-term pollutant peak events?

From the results of the AQI value outlier investigation in question 3 "*What are the pollutant concentrations underlying 'high/poor' air quality index values and outlier values?*" differences were noted among the AQI formulations in terms of their ability to respond to short term pollutant peak events. During O_3 and $PM_{2.5}$ peak pollutant concentrations, the HRBI 3hr and AQIONT formulations that are based on shorter pollutant averaging times were associated with increased AQI values. However, during NO_2 or SO_2 peak pollutant concentrations the AQIONT did not result in 'high/poor' air

quality categorizations. Only the HRBI 4p 3hr formulation classified those hours as 'high/poor'. With the HRBI 2p formulations the potential for capturing these NO_2 or SO_2 pollutant peaks is not even possible since these pollutants are not included in the formulation. The other formulations based on 24hr pollutant averaging times, tend to average out these peak pollutant concentrations. Thus, only those formulations with shorter pollutant averaging times will respond to peak pollutant concentrations lasting for only a short duration.

In the subsequent discussion section an overall assessment of the analytical results is made to summarize the observed analytical advantages and disadvantages of the different AQI formulations examined. Further to this assessment is also an assessment of each index formulation in relation to the AQI shortcomings described in section one of this thesis:

- *The AQI is not a health based index.* Although all of the formulations are intended to serve as public health information tools for air quality, the HRBI and S&T_Hyb formulations are the only formulations that are directly based on air pollution health-risk evidence. The other formulations are based on air pollution *standards,* which are not in accord with current health research evidence showing no threshold for the effects of air pollution on human health.
- *Outdated Air Quality Objectives.* Some of the *standards* used in the standards based indices (i.e. AQIONT, AQIEPA, S&T_ONT) have been updated. One example is the addition of $PM_{2.5}$ to the AQIONT and AQIEPA indices. However, *standards* for other pollutants such as NO_2 and SO_2 have not undergone regular

updating. The HRBI formulations do not rely on the use *standards* and have been designed to incorporate current air pollution health risk evidence.

- *Advances in air pollution health effects research.* One of the advances in air pollution health effects research that has been incorporated into all of the indices is the addition of $PM_{2.5}$ as a variable component defining the index formulation. However, as previously mentioned the no threshold effect of air quality health risk has only been reflected in the HRBI 4poll indices.
- *Single pollutant driven.* The AQIONT and AQIEPA indices continue to use single pollutant driven formulation approaches with no consideration for the effect of multiple pollutant contributions to air quality. The HRBI and Root Sum Exponential formulations have been designed with this consideration in mind.
- *Monitoring, reporting and forecasting technology improvements are not reflected in the AQI.* Currently, hourly pollutant concentrations are available for the majority of pollutants in the majority of Canadian cities. The AQIONT and HRBI 3hr formulations rely on short-term pollutant averaging times and as was commented in Question 10, these formulations enable the best capture of short term pollutant peak events. Thus, these formulations are more in line with real-time reporting of air quality conditions based on the air pollution monitoring data available. In terms of reporting and forecasting, these two issues are beyond the scope of the analytical comparison covered in this thesis.
- *Lack of a useful communication system.* The communication systems for each index formulation have not been assessed in this thesis, thus an evaluation is not possible.

- *Ambiguous descriptive categories.* Throughout this analytical comparison, the description of air quality categories has been referred to as 'high/poor' or 'low/good'. This thesis has not examined the ambiguousness of these categorizations, but in the General Discussion section of this thesis (Section 7.0), a discussion is presented on the appropriateness of using these categories to describe air quality conditions to the public.
- *No evaluation system.* Similarly, this thesis has not examined whether an evaluation process exists with each AQI. This thesis itself, has attempted to present some results to be used for the evaluation of these indices.

A preliminary assessment of user-considerations in terms of transparency, complexity and feasibility was conducted in the review of AQI formulations in section 4.0 to narrow down the potential AQI formulation options to be evaluated in the analytical comparison. Although a comprehensive assessment of user-considerations is not included in this thesis, a brief discussion on user-considerations is presented here.

All of the AQI formulation options examined are transparent in their formulation approaches with accompanying documentation detailing the specific AQI formulation. However, the HRBI formulation provides a detailed rationale and documentation of developmental work underlying the formulation. With regards to complexity, the Root Sum Exponential formulations (S&T) still require further development work to be applied as usable AQI formulations. The AQIONT and AQIEPA formulations are currently used in practice and therefore represent less complex options for application since they already have a history of use. However, they do not fully address all of the AQI shortcomings described above. The HRBI formulations present a new option for

AQI formulation and still require some additional refinement to address some of the time-averaging clarifications related to the 3-hour formulations thus presenting some issues with complexity for this new formulation. Yet, the underlying health risk basis for the index is in line with current air pollution health effects research addressing one of the main AQI shortcomings. All of the index formulations contain pollutants and pollutant averaging times that are currently available from Canadian air pollution monitoring stations. However, with a new AQI formulation, there are additional resource requirements to develop a new AQI messaging model and educate the public.

6.5 Discussion

The results of the analytical comparisons present a preliminary exploration of the characteristics of the different AQI formulations. A number of similarities and differences were revealed through the analyses that can be translated into strengths and weaknesses for the different formulations. Notably one of the most significant differences among the formulations revealed in the descriptive analysis is the categorization of air quality conditions over time for each Ontario monitoring site. A large gap was observed between the percentage of hours classified to 'high/poor' air quality categories among the HRBI and S&T_ONT formulations with the AQIONT, AQIEPA and S&T_Hyb formulations. The HRBI and S&T_ONT formulations classified up to 30 percent more hours as 'high/poor'. Discrepancies in air quality categorizations were even observed for those hours associated with the maximum AQI value and the second highest AQI value for the different formulations. This result suggests that there is a failure to categorize air quality accurately in at least one or more of the AQI formulations.

In further investigations to try and understand these differences the importance of three key factors was highlighted: multiple pollutant approach, pollutant time-averaging and pollutant weighting. The multiple pollutant approach applied in the HRBI formulations revealed the importance of the additive contribution of pollutants by demonstrating that even moderately high pollutant concentrations could result in 'high/poor' AQI values. This was not observed with the maximum operator formulation approaches, where the AQIONT and AQIEPA formulations rely on singularly high pollutant concentrations. The importance of the multi-pollutant influence was also noted in comparisons of the HRBI 4p formulations versus the HRBI 2p formulations. The additional influence of NO_2 and SO_2 in the HRBI 4p formulations resulted in a greater number of hours classified to 'high/poor' air quality categorizations. Upon more detailed investigation, certain hours were identified where peak pollutant concentrations were observed solely for these pollutants that resulted in 'high/poor' air quality designations. This demonstrates the importance of NO_2 and SO_2 as pollutant drivers for the HRBI. Thus, there is an analytical weakness in the HRBI 2p formulations that neglect to include these pollutants. The HRBI formulations with the same pollutant number, rather than pollutant averaging time were also most similar in their air quality categorizations; as a result, associating a greater importance with the multi-pollutant influence than pollutant averaging times. Nevertheless, time-averaging of pollutants was another important factor that translated into differing results among the AQI formulations. Formulations based on shorter pollutant averaging times were most sensitive to peak pollutant concentrations enabling them to reflect these peak events in their AQI values and resulting in differences in air quality categorizations even with only very short-term peak pollutant

concentrations. From a public health point of view, this could be particularly important for sensitive populations that are vulnerable to air quality conditions, even with only short-term exposures. Additionally, there is an increasing demand for real-time air quality reporting, necessitating the inclusion of shorter pollutant averaging times. Still, the short-term pollutant averaging times employed in the AQIONT did not result in 'high/poor' air quality categorizations during NO_2 or SO_2 peak pollutant concentrations. Only the HRBI 4p 3hr formulation classified those hours with higher NO_2 and SO_2 concentrations as 'high/poor'. This could be attributed to the multi-pollutant influence incorporated in the HRBI 4p 3hr formulation; however, the relative pollutant weighting or pollutant 'standard' associated with NO_2 and SO_2 would also help explain this difference. The pollutant 'standards' for NO_2 and SO_2 used in the AQIONT rely on the Ontario Ambient Air Quality Criteria, which are currently outdated and do not reflect current health evidence that reports health effects occurring at concentrations below these prescribed levels. In contrast, the HRBI 4p 3hr formulation relies on current health evidence and associates a health risk to concentrations below the prescribed levels of the AQIONT. Thus, there is a difference between these formulations in their consideration of what concentrations constitute a public health risk and consequently poor/high air quality categorizations. Hence, pollutant weighting is an additional factor contributing to the observed differences between the AQI formulations. It was found that even when pollutant concentrations were the same across formulations and there were only minor multi-pollutant influences from other low concentration pollutants, the AQI formulations still differed in their air quality categorizations. This underscores a key difference among

the formulations in their differing pollutant weighting, translating into a varied assigned importance attributed to each pollutant.

These differences question the accuracy of each AQI formulation and their ability to avoid ambiguous and eclipsed air quality categorizations. Based on the criticisms already associated with the maximum operator AQI formulations, current research that has revealed an additive and non-threshold effect of pollutants, and the vastly different air quality categorizations for the AQIONT and AQIEPA with the HRBI and Root Sum Exponential formulations, it is suggested that the maximum-operator AQI formulations are falsely declaring air quality conditions as 'good' or 'moderate' when in fact the conditions are 'high/poor'. Thus, the purpose of the AQI is not being upheld by improperly representing the state of air quality conditions for the public to be informed and protect themselves. On the other hand, the elevated number of hours associated with 'high/poor' air quality conditions observed with the HRBI and S&T_ONT formulations could be classifying less polluted air as highly polluted. Although possible, for the HRBI formulations at least, the health evidence base underlying these formulations and the results of the pollutant concentration investigation for high outlier HRBI values would suggest otherwise. Of course, a 30 percent increase in 'high/poor' air quality categorizations would likely be met with fear or skepticism by the public. Consequently, the corresponding AQI messaging system for an improved AQI needs to be considerate of these factors where an adjustment of the grouping categorizations may be required.

Not all analyses revealed differences among the formulations. All of the formulations reflected their conceptual basis in declaring increasingly higher pollutant concentrations with increasingly *worse* air quality index values. However, it could be

argued that this was not entirely true for the AQIONT and AQIEPA formulations in that increasingly higher pollutant concentrations among multiple pollutants did not result in higher AQI values, since only one pollutant concentration is reflected in the final AQI value. Likewise, all of the formulations correlated at least moderately well with each other, displaying overall consistency among the formulations. In addition, all of the formulations showed that $PM_{2.5}$ and O_3 were considered pollutant "drivers" during hours that were categorized as 'high/poor' air quality. For the AQIONT and AQIEPA formulations that include CO, CO was never found to be the pollutant driver during hours with 'high/poor' AQI values. Moreover, city and seasonal differences were observed among all formulations. This reflected each index formulation's ability to detect changes for air quality conditions with known variations. Finally, it was shown that among all formulations CO was not an important pollutant for driving air quality categorizations.

6.5.1 Potential Limitations

For the discussion of analytical limitations, probably the most important consideration is that of validity. The measurements used in this analysis represent physical phenomena and rely on standardized instruments for their measurement. Thus, the many types of bias often associated with measurement in epidemiological studies such as investigator bias or recall bias are not applicable in this analysis. In general, the use of pollutant data from different Ontario monitoring sites generated similar analytical results under the different investigations allowing for some of the general conclusions described above to be reached. However, there were some observed differences between the cities in terms of pollutant drivers and the ranking of formulations for the percentage

of hours classified to 'high/poor' air quality conditions. Consequently, there are some limitations in generalizing the results to a Canada wide context. Furthermore, all of the sites that were examined represented urban centres in Ontario. Hence, even though there are known differences in terms of the geography, industrial activity and transportation patterns for these cities, there are limitations in the capacity to extend the analytical results to other Canadian provinces and rural areas. Despite this, the size of the dataset and its minimal number of missing and invalid values along with the level of analysis at the hourly level, allow for great variability and assessment of these varied air quality conditions. Future analysis should focus on pilot testing the HRBI 4p formulations in other Canadian sites. If these future results attenuate some of the site specific results, perhaps customization of the HRBI for some sites is necessary.

Another limitation to this analysis is the incomplete calculation of the Root Sum Exponential formulations and the use of 'interim' HRBI formulations. The incompleteness of the Root Sum Exponential formulations did affect the capacity to quantitatively interpret some of the results. Still, a qualitative assessment was possible. The HRBI formulations continue to be refined by Health Canada and thus the specific HRBI formulations examined in this thesis may not be entirely representative of subsequent formulations. However, the underlying basis of the formulation will remain the same allowing for the generalization of the key findings. Along these lines, only selected formulations were chosen for inclusion in this analytical comparison and a more thorough comparison of other indices could have revealed other notable strengths or weaknesses among the formulations. Yet, in light of these limitations, the reader is drawn back to the objective of this analytical comparison, that is, to identify important

differences in some of the approaches towards AQI formulation that can be translated into strengths and weaknesses deserving attention.

6.6 Conclusions

This analytical comparison has shown that there are some distinct deficiencies with the maximum operator approach towards AQI formulation and some distinct advantages of the HRBI 4p formulations. The results highlight the following strengths of the HRBI 4p formulations: 1) the ability to reflect the additive contribution of pollutants by employing a multiple pollutant approach; 2) a non-threshold response for individual pollutants in categorizing air quality conditions as 'high/poor'; 3) the alignment of increasingly higher pollutant concentrations with increasingly 'high/poor' air quality categorizations; 4) the capacity to capture shorter-term pollutant peak events through the use of shorter-term pollutant averaging times; 5) representation of each of the index variables in the final AQI values; and 6) the direct-use of current air pollution health risk evidence for the development of an alternative AQI formulation for Canada. Yet, some of the characteristics of the HRBI such as the greater number of 'high/poor' air quality categorizations need to be considered in the context of real-word application. This represents a substantial shift that would require special attention in the communication messaging system.

7.0 GENERAL DISCUSSION

Following the results of this thesis work is an examination into the important and relevant findings of this work and the associated overall implications for AQI improvement in Canada. The analytical approach used in this thesis was that of theory and evidence informing analysis and practice. The background literature reviews on air pollution and human health, and air pollution health effects research, provided the context for developing an understanding of the significance and important considerations for the objectives of the work. The three main objectives of this thesis, addressed in the preceding sections, were guided from this background information but more importantly by objective four: to provide recommendations for review by the AQI Management Committee for a new Canadian AQI formulation. The result is three spheres of research evidence that are used to inform the final recommendations made in this thesis.

Firstly, it was determined that there was a need to understand the conceptual and measurement aspects of index development. The accompanying review highlighted the significance and value of indices for measurement simplification and communication. The process of index construction was identified as a systematic process with certain specified steps and considerations. Of equal importance were the practical considerations for implementation, since indices are representative of a societal interest and are most often intended for non-expert or public communication.

Secondly, the next sphere of research evidence addressed one of the steps highlighted in the first review by conducting a literature review of AQI formulation approaches. This review recognized the international acceptance and interest in AQI formulation. A number of different methods for AQI construction were identified.

Through a qualitative assessment of these methods, several options were identified for potential application to the Canadian context. These included the maximum operator approach, the Health Canada Health Risk Based Formulation approach and the Root Sum Exponential approach. Yet, a quantitative evidence base was lacking to provide a more thorough assessment of the options for Canadian AQI improvement.

With the use of the analytical considerations noted in the reviews, an analytical comparison of the various approaches towards AQI formulation was conducted. This established the final sphere of research evidence by identifying some of the analytical properties of the different AQI formulations. Through this analysis, distinct strengths and weaknesses among the formulations were observed. Additionally, this research component provided a detailed summary of the process of HRBI development. Analytical questions were developed to investigate the analytical properties of the different AQI formulations such as variable composition, variable relevancy and influence of pollutant time-averaging. Although there were some observed similarities among the formulations in terms of their declaration of increasingly worse air quality categorizations with increasing pollutant concentrations, their ability to reflect city and seasonal variations and a moderate correlation among all formulations, notable differences were also observed. Distinct strengths were noted for the HRBI 4p formulations in comparison to the other test formulations; AQIEPA, AQIONT and Root Sum Exponential formulations.

The realization of these three research objectives has contributed to the development of a strong evidence base for the final recommendations made in this thesis. A short summary of the results of the first three objectives is provided below. Then the

overall implications of the findings are discussed, and finally the recommendations for a new Canadian AQI formulation are presented.

7.1 Summary of Index Development

Indices represent simplifications of data that aim to provide more information than the variable components themselves. This is a challenge for index development in that the level of simplification needs to be accomplished so that the underlying truth is still maintained and the variable components need to be transformed in a way that still retains the significance of the variables in relation to the index measure. Index development begins with the definition of the purpose of the proposed index. A literature review should then be conducted to assess the availability of existing index options. Next, the conceptual basis for the index should be described to inform the next step of variable selection where the items making up the index are identified. The selected variables are then aggregated to form an index value. Following the development of the formulation an index needs to undergo validity, reliability and responsiveness testing. Index development is also guided by considerations relating to real-world application. These include an assessment of user considerations and feasibility, the development of a messaging system and any associated actions as well as the establishment of a process for index evaluation to ensure that the index continues to satisfy its intended purpose.

7.2 Summary of AQI Formulations

The available methods for AQI formulation are dominated by the aggregation of different pollutant sub-indices. Sub-indices are made up of observed pollutant

concentrations over their respective pollutant limit values. These limit values most often being prescribed air pollutant standards. Although the use of standards may be seen as being advantageous because the results are benchmarked, there are several important disadvantages of standard driven indices. The use of limit values is not in accordance with current air pollution health effects research that has shown harmful health effects at levels below prescribed standards with no observable threshold for health effects. Furthermore, the national and international diversity in standards emphasizes the fact that there is a great deal of uncertainty in the assignment of standards. Fuzzy set theory, population-level risk estimates of air pollution and health effects and exposure effectiveness were identified as alternatives to the standard-driven AQI formulations. The majority of the reviewed AQI formulations were determined to be either too complex, resource-intensive or were associated with significant analytical uncertainties that were likely not feasible for real-world application to the Canadian context. The maximum operator, Root Sum Exponential and health risk based formulations were identified as the most feasible options for Canadian AQI application and were thus chosen for a quantitative analytical comparison of strengths and weaknesses.

7.3 Summary of AQI Analytical Comparison

With the practical significance of this work being recommendations for an improved Canadian AQI, the analytical comparison of potential options for AQI formulation was necessary to showcase the differing analytical strengths and weaknesses of each AQI formulation. The multiple pollutant approaches towards AQI formulation adopted in the HRBI and Root Sum Exponential formulations displayed analytical

advantages over the AQIEPA and AQIONT maximum operator approaches in their ability to incorporate multiple pollutant effects. This resulted in a significantly greater number of hours with 'high/poor' AQI values. This difference immediately raised questions with regards to the ability of the existing AQI options (AQIONT and AQIEPA) in communicating accurate air quality information. With such notable differences, clearly there is a failure in one methodological formulation to categorize air quality accurately or arguably both methods, but the notable differences imply that there is greater accuracy in one AQI formulation approach. Current research has revealed that there is an additive effect of pollutants, thus associating greater confidence with the multiple pollutant approaches.

The four key pollutants: $PM_{2.5}$, O_3, SO_2 and NO_2, also have a stronger representation in the multiple pollutant approaches. This pollutant representation was particularly noted in the HRBI 4p formulations. The four key pollutants were all drivers of the final index value for the HRBI 4p formulations. The role of shorter term time averaging was also noted in that formulations with shorter-pollutant time averages tended to be better able at capturing shorter-term pollutant peak events. $PM_{2.5}$ and O_3 pollutant peak events were noted with the HRBI 3hr formulations and the AQIONT; however, only the HRBI 4p 3hr formulation translated those hours with higher NO_2 and SO_2 concentrations into pollutant peak events. The AQIONT's weighting of NO_2 and SO_2 in the form of standards is reflective of a decreased importance assigned to these pollutants for communicating 'high/poor' air quality events. Likewise, because the standards are outdated, the associated health risk is misrepresented. These analytical differences translate into significant real-world differences if existing AQI formulations are replaced

by the HRBI 4p formulations. Nevertheless, the HRBI 4p formulations showed significant empirical advantages over the other AQI formulations examined, necessitating further consideration.

7.4 Overall Implications

Air quality is both an immediately relevant and all-embracing topic to Canadian society. It is an issue of concern for Canadians as they continue to rank environmental concerns highly and have reiterated their desire for a public health communication tool informing them about current air quality conditions [133]. Air quality is also a significant public health issue as various adverse health effects have been linked to air pollution exposure, and it has the potential to affect all Canadians because the exposure is linked with a fundamental need for human life. Current Canadian AQIs designed for the purpose of mitigating the adverse health effects of air pollution by providing the public with information on air quality conditions, have faced multiple criticisms. Ultimately, they have failed to achieve their intended purpose by not being able to provide the public with accurate information on air quality conditions [1, 2]. Thus, the improvement of Canadian AQIs is a significant and relevant health policy for Canadians.

The practical significance of this work has founded the development of this thesis and provides a frame for the discussion of the thesis results and overall implications. As Spasoff [134] states in his summary of the assessment of potential interventions for health policy, it is necessary to consider the applicability of research results to the population for which the intervention is being considered. The improvement of Canadian AQIs is paralleled to an intervention in that it too has a specific aim to maintain and improve the

health of the population by providing more accurate information on air quality conditions. Spasoff also highlights the importance of assessing the feasibility of intervention implementation for the target population and the potential for nationwide application. These considerations are integrated into the discussion for an assessment of the implications of the work.

The results of this thesis work dictate a need and resolution for an improved Canadian AQI formulation. This action could take the form of further analytical investigation or the translation of these results into a health policy change in terms of moving forward with an improved Canadian AQI. Albeit, a deficiency free formulation has not been found, the HRBI has been shown to offer many significant improvements over existing AQIs and other AQI options. The health risk based AQI formulation addresses many of the currently identified deficiencies in existing AQIs and offers many important benefits that would facilitate its acceptance and implementation in Canada. The HRBI has been developed from a strong health evidence base. Its conceptual basis is founded on current air pollution health effects research by incorporating a multiple pollutant approach and relying on health risk information rather than air quality standards to quantify air quality conditions. In particular, the HRBI relies on Canadian health risk information making it particularly relevant for use within the Canadian context. Through a preliminary exploration of index properties, it was demonstrated that the HRBI has certain empirical advantages over the other AQI formulations examined. The HRBI incorporates the additive effect of multiple pollutant concentrations, is based on a non-threshold response for individual pollutants in categorizing air quality conditions and incorporates short-term pollutant time-averaging.

The index development process of the HRBI has also followed some of the key steps and considerations noted for index and AQI development. The purpose of the HRBI has been clearly stated and the conceptual basis has been detailed. A literature review on existing index options was also undertaken to identify potential AQI options for the Canadian context. The selection of variables and their aggregation was also quantitatively assessed using real-world Canadian data. The development of the HRBI has also progressed through collaboration with a variety of stakeholders across disciplines and interest groups. This has aided its analytical formulation development, but has also been beneficial for any future implementation. The formulation and process of development are transparent and developed in Canada, further garnering credibility and home-grown support.

Further support for the adoption of the HRBI formulation could be gained by pursuing additional analytical work to validate the HRBI's purpose of providing the public with accurate information on air quality conditions. Since the HRBI attempts to qualify the level of health risk associated with short-term exposures to outdoor air pollution, an analysis into the association of HRBI values with relevant health impacts besides mortality, such as emergency department visits or hospital admissions would help validate the index. Air pollution health risk evidence has revealed an association with increasing pollutant concentrations resulting in increased numbers of health-care visits. Thus, it would be expected that a similar association between health care visits and HRBI values would be observed. The HRBI and other AQI formulation approaches could be fit to a model representing health visits. Good model fit would support the validity of the index as a public health communication tool. Statistical analysis could involve the use of

existing time-series data where the day-to-day variability in pollutant concentrations for a community is related to the day-to-day variability in the rate of health care visits. Analysis examining the association of the HRBI with mortality is not suggested because of the inherent bias in using the same health outcome that was used to develop the HRBI formulation.

Validity testing of the HRBI and other formulations could also be pursued by examining the extent to which each formulation reflects meaningful changes in health risk through the input of various pollutant concentrations. This would involve defining, a priori, a set of air quality conditions which would be expected to be associated with meaningful differences in health risk. This could be done by using concentration response relationships for a variety of health outcomes, identifying what constitutes a meaningful change in health risk and then identifying the underlying air quality conditions associated with those health risks. Thus, essentially a back calculation of the associated air pollutant concentrations would be performed. Finally, these pollutant concentrations would be used to calculate the associated index values. One could then examine the extent to which each formulation reflects actual meaningful changes in health risk.

While the HRBI has been shown to have analytical advantages over other potential AQI options, it is also important to consider some of the implications associated with public health communication of this AQI. The AQI is first and foremost a public health communication tool and thus requires insight into any potential communication sensitivities. Throughout the analytical comparison, reference was made to the AQI categories of 'low/good' and 'high/poor'. In the context of a no threshold HRBI it is

important to consider the meaning of such categorizations and if they are fair interpretations for air quality communication.

The conceptual analytical basis of the HRBI is to translate the level of air pollution to a percent increase in air pollution associated mortality. The actual HRBI value is a scaled value, however air pollution associated mortality risk underlies the formulation. Thus, from one viewpoint it is difficult to understand how the use of value-laden categories can be philosophically and/or scientifically defended when even levels described as 'low/good' are associated with a certain risk of mortality. This challenging viewpoint is not unique to the issue of air quality communication but is common to the communication of nearly all health risk issues and is related to the field of risk acceptability.

Risk acceptability has been described as the concept that underlies judgments of safety (Kasperson, 1983) and risk acceptance is said to occur when the perceived benefits outweigh the perceived negative and harmful outcomes of a risk issue (Grasmuck and Scholz, 2005). Some argue that risk acceptance is more appropriately referred to as risk tolerance since the majority of the population is not fully informed on the risk issue at hand for full acceptance, and even if they were, it is difficult to accept the harmful outcomes and thus may only be tolerated (Kasperson, 1983; Sjoberg and Drottz-Sjoberg, 2001). Additionally, the term risk acceptability fails to capture the reluctance that is commonly associated towards risks. Tolerance on the other hand, expresses the willingness of individuals to live with a risk for certain benefits and with the understanding that it is being properly controlled (Geiger, 2005). The difficulty arises in

establishing this risk tolerance since the harmful outcomes associated with health risks are closely tied to emotions, ethics of decision making and fairness.

It is very common for moral values to be emphasized in risk debates when the risk outcome is death or harmful human health effects. Hattis and Anderson (1999) indicate that it is painful and difficult for human minds to make sense of tragic choices. It is troublesome for anyone to defend the acceptance of a risk resulting in death. Yet, the reality is that with or without risk tolerance criteria or risk categorizations we will continue to face health risks and will still be required to make decisions about how we choose to deal with these risks. Thus, what one also needs to consider is the moral value of the action that is being proposed for dealing with the risk. In this case, it is an AQI whose purpose is to inform the public about air quality conditions for public health risk protection. This is an arguably valuable and positive moral action since it stems from a concern to provide the public with a means of information for pubic health protection. Sjoberg and Drottz-Sjoberg (2003) have found that the moral value associated with the action is an important predictor of risk tolerance, even more important than the associated risk outcomes. This is also highlighted in a study by Arvai (2003) testing the hypothesis that public participation during decision-making about risks can lead to more widely accepted risk policies. The results of this study suggested that people are equally if not more interested in the process of risk policy decision-making, rather than the specific results of the decision-making process to determine their support for a risk policy decision. Hence, even though it is morally difficult to define risk acceptance criteria for quantitative estimates of health risk resulting in death, it is important to consider the

process and moral value of the action for which risk acceptance criteria or risk categorizations are proposed.

Albeit the HRBI is based on health risk, its purpose is not that of a health measurement tool for estimating the number of deaths attributable to air pollution; rather, the estimated health risk is used to inform the public about air quality conditions for public health safety. The value-laden categories of 'low/good' or 'high/poor' are a result of public preference for receiving air quality information in this format. In an Air Pollution Information Needs survey commissioned by Health Canada and conducted by Environics Research Group (2002) 43 percent of Canadians felt that air quality messages should be provided in a descriptive format (e.g. poor, fair, good, etc.). Of course it is not 'good' or 'low' if there is even one death as a result of air pollution; however this is not what the HRBI is trying to qualify. The descriptive risk categories are intended to provide a means for qualifying the level of risk in a relative sense, with no intention to assign a judged moral value for the associated level of health risk.

It could also be argued that there are also different value interpretations for the separate category labels of 'low', 'medium', and 'high' versus 'good', 'fair' and 'poor'. The former are less suggestive of the existence of a threshold[136], which would assist the public's understanding of air quality as a non- threshold health risk issue. In addition, 'low', 'medium' and 'high' descriptors are more in line with health risk terminology. Moreover, there are currently other recognizable environmental health indices such as the Canadian UV Index and the Pollen Index that use 'low', 'medium' and 'high' descriptive labeling. A move towards these descriptors for the HRBI would harmonize the terminology amongst these commonly reported environmental health indices. However,

it is also important to determine whether new labeling will alter peoples understanding of air quality health risk. Similarly, if it is determined that the public already understands labels such as 'good' in a relative sense without the assumption that there is a threshold for health risk, then there might be less need for revised descriptive air quality categories[136].

As the no-threshold HRBI implies, there is no level of air quality associated with zero risk as long as there are pollutants in the air. Thus, we need to somehow inform the public about air quality so they can protect themselves. This is the purpose of the HRBI and of any Canadian AQI, and the reasons stated above defend the use of the AQI value-laden risk categorizations.

Other potential communication sensitivities associated with a new Canadian AQI relate to transborder issues and implications. The introduction of a new Canadian AQI will not only result in air quality communication changes for Canada, but will also impact our U.S. neighbour with whom a history of transboundary air quality management already exists.

Air pollution has been recognized by both countries as a transborder issue. Air pollutants are able to travel distances as large as 100 to a few 1000 kilometres and many air pollutants remain in the atmosphere for long periods of time increasing the potential for them to be carried long distances[137, 138]. Thus, air pollution causing activities in one region can largely influence the air quality of a neighbouring region. Examples of this problem have been described in the Ontario MOE's report on transboundary air pollution in Ontario (2005). A significant amount of Ontario's smog is a result of U.S. contributions of O_3 and $PM_{2.5}$ and approximately 55 percent of air pollution health and

environmental damages in Ontario are attributed to transboundary air pollution[138]. Likewise, Ontario recognizes that its air polluting activities also contribute to transborder air pollution.

Some common ground has been established between both nations to regulate transborder air pollution; however, air quality communication approaches via an AQI have remained distinct. Even within Canada, the majority of the provinces have developed different AQIs over time as the national AQI was no longer meeting their needs. Still, the various AQIs employed have shared a common methodological basis with the maximum operator approach, but as was observed in the AQI analytical comparison the different maximum operator approaches also resulted in varied assessments of air quality. Adopting the HRBI as the new Canadian AQI will result in even greater variation among the Canadian and U.S. AQIs because of the HRBI's different methodological basis.

Some of the potential impacts in adopting the HRBI are a larger valuation of the air pollution problem than the U.S. PSI and a loss in common discussions regarding maximum operator pollutants. For those residents living in border cities between Canada and the U.S., there will likely be great variations between the AQI category assessments presented in the two different areas. This could be due to real pollutant concentration differences but also differences in the index categorizations themselves. This presents a dilemma for the public living in these bordering cities since they may sometimes be presented with what may seem to be contradicting messages for an area they feel is similar enough to be considered the same.

Another possible outcome of an increased number of 'high/poor' air quality categorizations on the Canadian side, is increased blame or strained relations with the U.S. for their air pollution causing activities. Attribution or blame laying, often follows bad news and it is often easiest to lay blame where a known problem already exists. In this case it is the transborder air pollution received from the U.S. These negative feelings may result in an increased desire for the public to become more involved and aware of air pollution health concerns, but may also lead to apathy in action since they may not be able to see any results of their changed actions when significant amounts of air pollution continue to be received from the U.S.

The education that will be required nationally will also be required internationally to help our partners in transboundary air quality management understand this new initiative. The possibility exists for the HRBI to be applied in the U.S. and elsewhere internationally. Since the HRBI is based on Canadian air pollution data and associated health risk, its use internationally will likely need country specific inputs to validate its use and translate it to their specific contexts. For example, pollutant concentrations, health effects and exposure opportunities may differ between countries resulting in a modified version of the HRBI. For those countries, having the political will to devote resources to air quality public health protection and improvement in their AQIs, the HRBI's methodological basis could arguably be applied.

Still, there are other factors contributing to a successful communication tool and because of international, cultural and governing differences the new HRBI may not necessarily translate to all international contexts. Some of the difficulties in trying to apply the HRBI internationally may be related to the political nature of decision-making.

Some countries including the U.S. have recently updated their AQIs and another change may be too soon while they are still evaluating their current efforts. Additionally, the fact that this new AQI is not 'homegrown' may present difficulties in acceptance where each country has already devoted their own resources in this area. Further, international acceptance of an idea or new methodology will often demand higher standards for acceptance since there are many more stakeholders involved and different political agendas at action. Although an increased number of parties reviewing and scrutinizing ideas and methods is beneficial in that increased feedback and considerations are provided, it also presents hard demands and can make efficient progress limited.

In summary, the purpose of Canadian AQI improvement has been to produce a public policy utilization tool to assist the public in obtaining accurate information on outdoor air quality conditions. In this preliminary assessment of index properties the HRBI was shown to have a number of advantages over existing AQIs and other AQI options. Yet, before the HRBI is considered for implementation in the Canadian context, there is additional development work required. The HRBI formulation requires further refinement of the interim formulations presented in this thesis to address some of the time-averaging issues related to the 3 hour formulations. Moreover, as previously stated, it is important to consider the applicability and feasibility of research results to the population for which the intervention is being considered. The Canadian society at large along with the federal and provincial governments would be the users of an improved AQI formulation. Pilot testing the HRBI with other Canadian air quality data would help further assess some of the HRBI's strengths and weaknesses. Of equal importance, is the development of a corresponding messaging system that is associated with easily

understandable, accessible and recognizable messages. Along these lines, public education surrounding an improved AQI formulation and its use would be required. This additional work needs to be considered in the context of existing Canadian AQI formulations and the public's knowledge and acceptance of them. The introduction of an improved AQI needs to be considerate of existing systems and challenges. There is also time sensitivity to this process of improvement as a number of deficiencies have been identified with the current AQI formulations.

It is also important to consider the data requirements for the application of a new formulation across Canada. The majority of Canadian cities possess the data requirements for calculating the HRBI and still the possibility of adapting the formulation to meet data options also exists by incorporating historical background pollutant concentrations for those pollutants where continuous monitoring has ceased. The implementation of an improved AQI formulation to the Canadian context also requires that the process of AQI improvement itself occur at more frequent intervals. This process could be aligned with the process of updating the Canada Wide Standards for PM and O_3 to ensure that there is accountability for the updates and aid with the coordination of these two processes. A final practical consideration to assist with the successful application of an improved AQI formulation is through the development and communication of national environmental health goals. As Frankish et al. [135] had suggested for the implementation of health impact assessment in Canada, national environmental health goals would support the AQI's purpose and help establish accountability for its fulfillment and continued support.

7.5 Recommendations

Based on the research evidence summarized in this thesis work, it is recommended that:

1) An improved AQI formulation is implemented in Canada. The improved Canadian AQI formulation should:
    1.1) Be based on a multiple pollutant model approach incorporating $PM_{2.5}$, O_3, NO_2 and SO_2;
    1.2) Be based on current air pollution health effects evidence through the use of population-level health risk estimates and not prescribed limit values; and
    1.3) Incorporate short-term air pollutant concentrations for reporting at a minimum of every 3 hours.
2) Further descriptive analysis and validity testing be pursued comparing a final HRBI formulation with existing AQI formulations.
3) An associated health messaging system for an improved Canadian AQI formulation should be established using a collaborative and evidence-based approach.
4) The principal stakeholders that will be responsible for managing the implementation of an improved Canadian AQI formulation be educated on the improved formulation and its messaging system.
5) The final improved Canadian AQI formulation be pilot-tested at several different Canadian locations to assess its real-world application, gain further acceptance and identify areas for improvement.

6) A process for review and evaluation of the final improved Canadian AQI formulation should be established in conjunction with the Canada Wide Standards for PM and O_3.

7) National environmental health goals should be established to support the AQI's purpose, maintain nationally uniform messages on air quality and health, and help establish accountability.

8.0 CONCLUSIONS

The improvement of Canadian AQIs is an important public health policy for Canadians. It seeks to address an issue of wide-social concern that has true public health significance, as there has been increasing evidence showing that existing Canadian AQIs are not satisfying their purpose of providing the public with accurate information on air quality conditions. Although this improvement process has been initiated with notable progress, there is an absence of information on the conceptual and measurement aspects of index development, the current state of knowledge and practices relating to air quality index formulation and application, and an analytical comparison of various approaches towards AQI formulation. Through a research synthesis of index and AQI formulation development and a preliminary analytical comparison of AQI properties among different AQI formulation options, this research sought to address some of these gaps. The result is a contribution to the health evidence base for AQI improvement in Canada. Furthermore, seven recommendations for Canadian AQI improvement were presented for consideration by the AQI Management Committee. In short, there were a number of advantages identified with the health risk based formulation approach developed by Health Canada. Several characteristics possessed by the interim HRBI formulation were put forward as recommendations for an improved Canadian AQI formulation; however further analysis and validity testing is suggested using a final HRBI formulation. With continued support and commitment from the members of the Canadian AQI improvement committee and Health Canada to pursue the improvement of Canadian AQIs, the purpose of the AQI in providing the public with accurate air quality information will be realized.

REFERENCES

1. Toronto Public Health. Toronto Air Quality Index: Health Links Analysis. Toronto; 2001.
2. Environment Canada. Progress Report to the 2002 Toronto Smog Summit: Steps Towards Improving Canadian Air Quality Indices; 2002. http://www.msc-smc.ec.gc.ca/CAQI/phase1/2002smogsummit_e.cfm (Jan. 2004).
3. Environment Canada. Canadian Air Quality Index: Frequently Asked Questions; 2002. http://www.msc-smc.ec.gc.ca/CAQI/faq_e.cfm#Why (Jan. 2004).
4. Hewings J. Air Quality Indices: A Review. Toronto: Pollution Probe; 2001.
5. Toronto Public Health. Condition Critical: Fixing Our Smog Warning System. Toronto; 2001.
6. World Health Organisation. Air Pollution. Fact Sheet No.187; 2000. http://www.who.int/inf-fs/en/fact187.html (July 2003).
7. Judek S, Jessiman B, Stieb D, Vet R. Estimating Number of Excess Deaths in Canada due to Air Pollution; 2005. http://www.hc-sc.gc.ca/ahc-asc/media/nr-cp/2005/2005_32bk2_e.html (Nov. 2005).
8. Ontario Medical Association. The Illness Costs of Air Pollution; 2005. http://oma.org/phealth/smogmain.htm#illness.
9. Health Canada. Centre for Chronic Prevention and Control Chronic Respiratory Diseases: Facts and Figures - Ashma; 2004. http://www.phac-aspc.gc.ca/ccdpc-cpcmc/crd-mrc/facts_asthma_e.html (June 2004).
10. Statistics Canada. Population projections for Canada, provinces and territories, 2000-2026. Catalogue no. 91-520-X1B; 2001. http://www.statcan.ca/bsolc/english/bsolc?catno=91-520-X (June 2004).
11. World Health Organisation. Guidelines for Air Quality; 2000. http://www.who.int/peh/ (Oct. 2003).
12. Katsouyanni K. Ambient air pollution and health. Br Med Bull 2003;68:143-56.
13. Colls J. Air Pollution 2nd edition. New York: Spon Press; 2002.
14. McConnell R, Berhane K, Gilliland F, London SJ, Islam T, Gauderman WJ, et al. Asthma in exercising children exposed to ozone: a cohort study. Lancet 2002;359(9304):386-91.
15. Health Canada. Human Health Effects of Ozone: Update in Support of the Canada-Wide Standards for Particulate Matter and Ozone; 2003. http://www.ccme.ca/initiatives/standards.html?category_id=61#170 (May 2004).
16. Schwartz J. Air pollution and children's health. Pediatrics 2004;113(4 Suppl):1037-43.
17. Godish T. Air Quality 4th edition. New York: Lewis Publishers; 2004.
18. Brunekreef B, Holgate ST. Air pollution and health. Lancet 2002;360(9341):1233-42.
19. Hoppe P, Praml G, Rabe G, Lindner J, Fruhmann G, Kessel R. Environmental ozone field study on pulmonary and subjective responses of assumed risk groups. Environ Res 1995;71(2):109-21.
20. Koren H, Bisesi M. Handbook of Environmental Health Volume 2. York: Lewis Publishers; 2003.
21. Health Canada. Human Health Effects of Fine Particulate Matter: Update in Support of the Canada-Wide Standards for Particulate Matter and Ozone; 2003. http://www.ccme.ca/initiatives/standards.html?category_id=61#170 (May 2004).

22. USEPA. EPA's Updated Air Quality Standards for Smog (Ozone) and Particulate Matter; 2002. http://www.epa.gov/ttn/oarpg/naaqsfin/ (July 2004).
23. Vedal S. Update on the health effects of outdoor air pollution. Clin Chest Med 2002;23(4):763-75, vi.
24. Harrop DO. Air Quality Assessment and Management: A Practical Guide. New York: Spon Press; 2002.
25. Allred EN. et al. Acute Effects of Carbon Monoxide Exposure on Individuals with Coronary Artery Disease: Health Effects Institute; 1989. Report No.: 25. 25.
26. Last J, (ed). A Dictionary of Epidemiology 4th edition. Toronto: Oxford University Press; 2001.
27. Dominici F, McDermott A, Zeger SL, Samet JM. On the use of generalized additive models in time-series studies of air pollution and health. Am J Epidemiol 2002;156(3):193-203.
28. Ramsay TO, Burnett RT, Krewski D. The effect of concurvity in generalized additive models linking mortality to ambient particulate matter. Epidemiology 2003;14(1):18-23.
29. Kelsey J.L. et al. Methods in Observational Epidemiology. New York: Oxford University Press; 1996.
30. Shi L. Health Services Research Methods. Albany, N.Y.: Delmar Publishers; 1997.
31. European Centre for Environment and Health. Quantification of the Health Effects of Exposure to Air Pollution. Bitlhoven, The Netherlands: WHO; 2000.
32. Stroup DF, Berlin JA, Morton SC, Olkin I, Williamson GD, Rennie D, et al. Meta-analysis of observational studies in epidemiology: a proposal for reporting. Meta-analysis Of Observational Studies in Epidemiology (MOOSE) group. Jama 2000;283(15):2008-12.
33. Egger M, Smith GD, O'Rourke K. Rationale, potentials, and promise of systematic reviews. In: Egger M, Smith GD, Altman JD, (eds). Systematic Reviews in Health Care: Meta-Analysis in Context. Cornwall: BMJ Publishing Group; 2001.
34. Bailar JC, 3rd. The promise and problems of meta-analysis. N Engl J Med 1997;337(8):559-61.
35. Blair A, Burg J, Foran J, Gibb H, Greenland S, Morris R, et al. Guidelines for application of meta-analysis in environmental epidemiology. ISLI Risk Science Institute. Regul Toxicol Pharmacol 1995;22(2):189-97.
36. Egger M, Dickersin K, Smith GD. Problems and limitations in conducting systematic reviews. In: Egger M, Smith GD, Altman JD, (eds). Systematic Reviews in Health Care: Meta-Analysis in Context. Cornwall: BMJ Publishing Group; 2001.
37. Sterne NAC, Egger M, Smith GD. Investigating and dealing with publication and other biases. In: Egger M, Smith GD, Altman JD, (eds). Systematic Reviews in Health Care: Meta-analysis in Context. Cornwall: BMJ Publishing Group; 2001.
38. DerSimonian R, Levine RJ. Resolving discrepancies between a meta-analysis and a subsequent large controlled trial. Jama 1999;282(7):664-70.
39. Ioannidis JP, Cappelleri JC, Lau J. Issues in comparisons between meta-analyses and large trials. Jama 1998;279(14):1089-93.
40. LeLorier J, Gregoire G, Benhaddad A, Lapierre J, Derderian F. Discrepancies between meta-analyses and subsequent large randomized, controlled trials. N Engl J Med 1997;337(8):536-42.

41. Stieb DM, Judek S, Burnett RT. Meta-analysis of time-series studies of air pollution and mortality: effects of gases and particles and the influence of cause of death, age, and season. J Air Waste Manag Assoc 2002;52(4):470-84.
42. Stieb DM, Judek S, Burnett RT. Meta-analysis of time-series studies of air pollution and mortality: update in relation to the use of generalized additive models. J Air Waste Manag Assoc 2003;53(3):258-61.
43. Samet JM, Zeger SL, Dominici F, Curriero F, Coursac I, Dockery DW, et al. The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and mortality from air pollution in the United States. Res Rep Health Eff Inst 2000;94(Pt 2):5-70; discussion 71-9.
44. Kircher T, Nelson J, Burdo H. The autopsy as a measure of accuracy of the death certificate. N Engl J Med 1985;313(20):1263-9.
45. Maudsley G, Williams EM. "Inaccuracy' in death certification--where are we now? J Public Health Med 1996;18(1):59-66.
46. Beard CM, Yunginger JW, Reed CE, O'Connell EJ, Silverstein MD. Interobserver variability in medical record review: an epidemiological study of asthma. J Clin Epidemiol 1992;45(9):1013-20.
47. Delfino RJ, Becklake MR, Hanley JA. Reliability of hospital data for population-based studies of air pollution. Arch Environ Health 1993;48(3):140-6.
48. Martinez F, Sunyer J, Anto JM. Reliability of a monitoring system for respiratory emergency room admissions. Eur Respir J 1993;6(3):337-41.
49. Oleckno WA. Essential Epidemiology: Principles and Applications. Illinois: Wavelend Press; 2002.
50. Health Effects Institute. Revised Analyses of Time-Series Studies of Air Pollution and Health. Special Report. Boston: Health Effects Institute; 2003. http://www.healtheffects.org/Pubs/TimeSeries.pdf.
51. Goldberg MS, Burnett RT. Revised Analysis of the Montreal Time-Series Study. Boston: Health Effects Institute; 2003.
52. Joliffe IT. Principal Component Analysis 2nd edition. New York: Springer-Valley Inc.; 2002.
53. Jackson JE. A user's guide to principal components. Toronto: John Wiley & Sons, Inc.; 1991.
54. Hyvarinen A, Karhunen J, Oja E. Independent Component Analysis. Toronto: John Wiley & Sons, Inc.; 2001.
55. Cassino C, Ito K, Bader I, Ciotoli C, Thurston G, Reibman J. Cigarette smoking and ozone-associated emergency department use for asthma by adults in New York City. Am J Respir Crit Care Med 1999;159(6):1773-9.
56. Dockery DW, Pope CA, 3rd, Xu X, Spengler JD, Ware JH, Fay ME, et al. An association between air pollution and mortality in six U.S. cities. N Engl J Med 1993;329(24):1753-9.
57. Samet JM, White RH. Urban air pollution, health, and equity. J Epidemiol Community Health 2004;58(1):3-5.
58. Lipfert FW. Air pollution and poverty: does the sword cut both ways? J Epidemiol Community Health 2004;58(1):2-3.

59. Finkelstein MM, Jerrett M, DeLuca P, Finkelstein N, Verma DK, Chapman K, et al. Relation between income, air pollution and mortality: a cohort study. Cmaj 2003;169(5):397-402.
60. Lin M, Chen Y, Villeneuve PJ, Burnett RT, Lemyre L, Hertzman C, et al. Gaseous air pollutants and asthma hospitalization of children with low household income in Vancouver, British Columbia, Canada. Am J Epidemiol 2004;159(3):294-303.
61. Krewski D, Burnett RT, Goldberg MS, Hoover K, Siemiatycki J, Jerrett M, et al. Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality. Cambridge: Health Effects Institute; 2000.
62. Daniels MJ, Dominici F, Zeger SL, Samet JM. The National Morbidity, Mortality, and Air Pollution Study Part III: PM10 Concentration-Response Curves and Thresholds for the 20 Largest US Cities. Cambridge: Health Effects Institute; 2004.
63. Ott WR. Environmental Indices: Theory and Practice. Michigan: Ann Arbor Science Publishers Inc.; 1978.
64. Alfsen K, Saebo H. Environmental Quality Indicators: Background, Principles and examples from Norway. Environmental Resource Economics 1993;3:415-435.
65. Allen RGD. Index Numbers in Theory and Practice. New York: MacMillan Press Ltd.; 1975.
66. Leibowitz SG, Hyman JB. Use of scale invariance in evaluating judgement indicators. Environmental Monitoring and Assessment 1999;58(3):283-303.
67. Commission on Geosciences Environment and Resources. Ecological Indicators for the Nation: National Academy Press; 2000.
68. Lenz R, Malkina-Pykh IG, Pykh Y. Index 98 Workshop - Introduction and overview. Ecological Modelling 2000;130(1-3):1-11.
69. McDowell I, Newell C. Measuring Health: A Guide to Rating Scales and Questionnaires. New York: Oxford University Press; 1996.
70. Briggs D. Environmental Health Indicators: Framework and Methodologies: World Health Organisation; 1999. Report No.: WHO/SDE/OEH/99.10. WHO/SDE/OEH/99.10. www.who.int/docstore/peh/archives/EHindicators.pdf.
71. Environment Canada, Health Canada. Developing environmental public health indicators in Canada(draft). In: Conference of European Statisticians; 2001 October 1-4, 2001; Ottawa, Canada; 2001. http://www.unece.org.stats/documents/2001/10/env/wp.24e.pdf.
72. DeVellis RF. Scale Development: Theory and Applications. California: Sage Publications; 1991.
73. Netemeyer RG, Bearden WO, Sharma S. Scaling Procedures: Issues and Applications. California: Sage Publications; 2003.
74. Spector PE. Summated Rating Scale Construction: An Introduction. California: Sage Publications; 1992.
75. Diamantopoulos A, Winklhofer HM. Index construction with formative indicators: An alternative to scale development. Journal of Marketing Research 2001;38(2):269-277.
76. Goldberg E. Aggregated Environmental Indices: Review of Aggregation Methodologies in use: Organisation for Economic Co-operation and Development; 2002. http://www.oecd.org/findDocument/0,2350,en_2649_34283_1_119666_1_1_37465,00.html.
77. Miller DC, Salkind NJ. Handbook of Research Design and Social Measurement, 6th edition. California: Sage Publications; 2002.

78. Streiner D, Norman G. Health Measurment Scales: A Practical Guide to their Development and Use, 2nd edition. New York: Oxford University Press; 1995.
79. Ott WR, Thom GC. Critical-Review of Air-Pollution Index Systems in United-States and Canada. Journal of the Air Pollution Control Association 1976;26(5):460-470.
80. Garcia J, Colosio J. Air Quality Indices: Elaboration, Uses and International Comparisons. Paris: Les Presses de l'Ecole des Mines; 2002.
81. Kyle AD, Wright CC, Caldwell JC, Buffler PA, Woodruff TJ. Evaluating the health significance of hazardous air pollutants using monitoring data. Public Health Reports 2001;116(1):32-44.
82. Niemeijer D. Developing indicators for environmental policy: data-driven and theory-driven approaches examined by example. Environmental Science & Policy 2002;5:91-103.
83. Khordagui HK, Al-Ajmi DN. Application of indices for air quality management in Kuwait. Environmental Management 1996;20(1):151-158.
84. Bowling A. Measuring Health: A Review of Quality of Life Measurement Scales, 2nd edition. Philadelphia: Open University Press; 1997.
85. Swamee PK, Tyagi A. Formulation of an Air Pollution Index. Journal of the Air & Waste Management Association 1999;49:88-91.
86. Cheng WL, Kuo YC, Lin PL, Chang KH, Chen YS, Lin TM, et al. Revised air quality index derived from an entropy function. Atmospheric Environment 2004;38(3):383-391.
87. Oxford Concise English Dictionary. The Concise Oxford Dictionary of Current English. New York: Oxford Univeristy Press; 1995.
88. Bruno F, Cocchi D. A unified strategy for building simple air quality indices. Environmetrics 2002;13(3):243-261.
89. Rothman KJ, Greenland S. Modern Epidemiology, 2nd edition. Philadelphia: Lippincott-Raven Publishers; 1998.
90. Khanna N. Measuring environmental quality: an index of pollution. Ecological Economics 2000;35(2):191-202.
91. Hauser RM, Goldberger AS. The Treatment of Unobservable Variables in Path Analysis. In: Costner HL, (ed). Sociological Methodology. San Francisco; 1971. p. 81-117.
92. Nunnally JC, Bernstein IH. Psychometric Theory, 3rd edition. New York: McGraw-Hill; 1994.
93. Cairns J, McCormick PV, Niederlehner BR. A Proposed Framework for Developing Indicators of Ecosystem Health. Hydrobiologia 1993;263(1):1-44.
94. Krewski D, Burnett RT. Environmental Health Status Indicators: Issues and Approaches. In: McColl RS, (ed). Development of Environmental Health Status Indicators: Institute for Risk Research; 1992.
95. Bickerstaff K, Walker G. Clearing the Smog? Public Responses to Air-Quality Information. Local Environment 1999;4(3):279-294.
96. Willis J, Okunade AA. Reporting on Risks: The Practice and Ethics of Health and Safety Communication. Connecticut: Praeger Publishers; 1997.
97. Bottcher RW. Information needs related to extension service and community outreach. Environ Int 2003;29(2-3):337-40.
98. Cunningham WP, Stubbs HS. Information needs related to teaching about air quality. Environ Int 2003;29(2-3):331-6.

99. Johnson BB. Utility Customers' Views of the "Consumer Confidence Report" of Drinking Water Quality. Risk: Health, Safety & Environment 2000;11:309.
100. Smith KR. Why should an Air Pollution Index include exposure and how would it be done? In: CSE Workshop on Air Quality Index and Pollution Source Inventory; 2000 June 6-8, 2000; New Delhi, India; 2000. p. 3-4. http://www.cseindia.org/campaign/apc/pdf/abstract.pdf.
101. Chelani AB, Chalapati R, Phadke KM, Hasan MZ. Formulation of an air quality index in India. International journal of Environmental Studies 2002;59(3):331-342.
102. Stone SL. Structure of the U.S. Air Quality Index (AQI). In: CSE Workshop on Air Quality Index and Pollution Source Inventory; 2000 June 6-8, 2000; New Delhi, India; 2000. p. 5-9. http://www.cseindia.org/campaign/apc/pdf/abstract.pdf.
103. World Health Organization. Guidelines for Air Quality. Geneva; 2000. http://www.who.int/peh/.
104. Sengupta B, Sharma M, Shukla P, Maheshwari M. Air quality index for data interpretation and public information. In: CSE Workshop on Air Quality Index and Pollution Source Inventory; 2000 June 6-8, 2000; New Delhi, India; 2000. p. 13-14. http://www.cseindia.org/campaign/apc/pdf/abstract.pdf.
105. Thomas WA. Public Acceptance of an Air Quality Index. J. Environ. Educ. 1975;6(4):18-24.
106. Federal-Provincial Advisory Committee on Air Quality. Guidelines for the Index of the Quality of the Air: Environment Canada; 1992. Report No.: EN49-5/1-3E. EN49-5/1-3E.
107. Barbiroli G, Mazzaracchio P, Raggi A, Alliney S. A Proposal for a New Method to Develop Synthetic Quality Indexes for Air and Water. Journal of Environmental Management 1992;36(4):237-252.
108. Malakos M, Wong KFV. Proposed pollutant index to incorporate synergistic effects. International Journal of Environment and Pollution 1999;12(1):73-80.
109. Green AES, Rio DE, Hedlinger RA. Florida's Air Quality, Present and Future. Fla. Scientist 1978;41:182-190.
110. Fisher B. Fuzzy environmental decision-making: applications to air pollution. Atmospheric Environment 2003;37(14):1865-1877.
111. Srivastava A, Kumar R. Economic valuation of health impacts of air pollution in Mumbai. Environmental Monitoring and Assessment 2002;75(2):135-143.
112. Sterling TD, Pollack SV, Phair JJ. Urban hospital morbidity and air pollution. A second report. Arch Environ Health 1967;15(3):362-74.
113. Stieb D, Burnett RT, Smith-Doiron M, Chen Y, Goldberg M, Cakmak S, et al. Air Pollution, Mortality and Cardiorespiratory Hospital Admissions in 11 Canadian Cities, 1998-2000: Application to a Reformulated Air Quality Index. In. unpublished; 2003.
114. Cairncross EK, John J. Communicating Air Pollution Exposure: A Novel Air Pollution Index System Based on the Relative Risk of Mortality Associated with Exposure to the Common Urban Air Pollutants. In: World Clean Air and Environmental Protection Congress; 2004; London, UK; 2004.
115. Global Environmental Monitoring System. Estimating Human Expsosures to Air Pollutants in Smith (1993). Geneva: World Health Organization; 1982. Report No.: 69. 69.
116. Seika M, Metz N. Urban air quality management: the traditional vs. an exposure-based approach. Science of the Total Environment 1999;235(1-3):359-361.

117. Stieb DM, Doiron MS, Blagden P, Burnett RT. Estimating the public health burden attributable to air pollution: an illustration using the development of an alternative air quality index. J Toxicol Environ Health A 2005;68(13-14):1275-88.
118. Air Quality Index Health Aspects Working Group. Interim Report. Ottawa, Canada: Environment Canada; 2002.
119. Air Quality Index Management Committee. Steps Towards Improving Canadian Air Quality Indices: Progress Report to the 2002 Toronto Smog Summit: Environment Canada; 2002. http://www.msc-smc.ec.gc.ca/CAQI/phase1/2002smogsummit_e.cfm.
120. Burnett RT, Brook J, Dann T, Delocla C, Philips O, Cakmak S, et al. Association between particulate- and gas-phase components of urban air pollution and daily mortality in eight Canadian cities. Inhal Toxicol 2000;12 Suppl 4:15-39.
121. Burnett RT, Stieb D, Brook JR, Cakmak S, Dales R, Raizenne M, et al. Associations between short-term changes in nitrogen dioxide and mortality in Canadian cities. Arch Environ Health 2004;59(5):228-36.
122. Dominici F, Samet JM, Zeger SL. Combining evidence on air pollution and daily mortality from the 20 largest US cities: a hierarchical modelling strategy. Journal of the Royal Statistical Society Series a-Statistics in Society 2000;163:263-284.
123. Environment Canada. NAPS Network Summary; 2004. http://www.etcentre.org/naps/naps_summary_e.html (Oct. 2004).
124. Environment Canada. National Air Pollution Surveillance (NAPS) Network, air quality in Canada: 2001 summary and 1990-2001 trend analysis; 2004. Report No.: EN84-1/20O4E. EN84-1/20O4E. http://www.etc-cte.ec.gc.ca/publications/naps/NAPS_2001%20Summary_1990-2001_Trend_Analysis.pdf.
125. Air Quality Index Monitoring and Data Analysis Working Group. Interim Report. Ottawa, Canada: Environment Canada; 2002.
126. Dann T. Environment Canada. (Personal Communication). Recipient: Stieb D; 2004.
127. Health Canada. Personal Communication with Dr. Dave Stieb, Health Canada. (Personal Communication). Recipient: 2004.
128. Greenhouse JB, Iyenhar S. Sensitivity Analysis and Diagnostics. In: Cooper H, Hedges LV, (eds). The Handbook of Research Synthesis. New York: Russel Sage Foundation; 1994.
129. Saltelli A. Sensitivity analysis for importance assessment. Risk Anal 2002;22(3):579-90.
130. USEPA. Air Quality Index Reporting. 40 CFR Part 58 [FRL-6409-7] RIN 2060-AH92. Federal Register; 1999.
131. Ontario Ministry of Environment. A guide to the Ontario Air Quality Index System log 91-2206-047; 1991.
132. Ontario Ministry of Environment. Ontario Air Quality Index Equations received from Christina Cheng, Ontario Ministry of Environment. (Personal Communication). Recipient: 2004.
133. Environics Research Group. Development of Health-Based Air Quality Index for Canada. Ottawa; 2005. http://hc-sc.gc.ca/ewh-semt/pubs/air/out-ext/aqi-iqa/index_e.html.
134. Spasoff RA. Epidemiologic Methods for Health Policy. Toronto: Oxford University Press; 1999.
135. Frankish et al. Health Impact Assessment as a Tool for Population Health Promotion and Public Policy: UBC Institute of Health Promotion Research; 1996.

136. Decisionalysis Risk Consultants. Issues in Developing a Risk Communication Strategy for the Air Quality Index. Ottawa; 2002.
137. Bergin MS, West JJ, Keating TJ, Russell AG. Regional Atmospheric Pollution and Transboundary Air Quality Management. Annu. Rev. Environ. Resour. 2005;30:1-37.
138. Ontario Ministry of Environment. Transboundary air pollution in Ontario; 2005 June 2005.